

**THE USE OF DAIRY MANURE COMPOST FOR
SUSTAINABLE MAIZE (*Zea mays* L.)
PRODUCTION**

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Abstract

Intensive production systems for maize (*Zea mays* L.) based on the use of inorganic fertilisers are expensive and unsustainable, as their production is dependent on fossil fuels. Additionally, inorganic fertilisers are unable to maintain soil fertility over the long-term, and are related to environmental problems such as soil erosion and nitrate pollution of the ground water table. Moreover, high cost agrochemicals are either unavailable or too costly for small farmers in tropical countries, where maize is usually grown as a subsistence crop.

This research project examined the use of compost derived from dairy manure and cereal straw, renewable resources available on the farm, as an organic fertiliser for a sustainable maize production system. The effects of this compost on soil and plant nutrient content, and on maize and weed growth were studied, examining the various soil-plant interactions. The relevant literature was reviewed, comparing different production systems, and examining aspects of maize production, nutrient recycling and the effects and interactions of compost in the soil-plant system. Field and glasshouse experiments were carried out from 1993 to 1995 on Wye College Estate, UK, comparing the use of dairy manure compost and inorganic fertiliser in forage maize production. Soil chemical (nutrient content) and biological (microbial biomass and activity) aspects were analysed at several stages of maize development. Plant (maize and weed) nutrient content and biomass production were also determined. A laboratory experiment studied nitrogen mineralisation rates of dairy manure compost under controlled conditions. A further field experiment, conducted by the *Università degli Studi della Tuscia* in Viterbo, Italy, allowed comparisons of some results under different climatic conditions.

There was evidence that compost application could adequately supply maize nutrient requirements, by enhancing and sustaining soil fertility, with increased microbial biomass and nutrient levels. In general, maize biomass production was similar under both compost and chemical fertiliser addition, but a potential for higher maize dry matter yields with long-term compost application was suggested. In addition, compost was consistently associated with a lower potential for nitrate pollution of the ground water table.

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Table of Contents

Abstract.....	2
Acknowledgements	3
Dedication	4
Table of Contents	5
List of Tables	12
List of Figures	15
List of Plates	18
Abbreviations and Symbols	19
 Chapter 1. Introduction.....	20
1.1 General aspects	20
1.2 Objectives of this research	21
1.3 Structure of thesis	23
 Chapter 2. Literature Review	25
2.1 Maize production.....	25
2.1.1 Climatic requirements	25
2.1.2 Agronomic and physiological aspects.....	26
2.1.3 Factors affecting maize productivity	27
2.1.4 Nutrient requirements	28
2.2 Historical background of production systems	30
2.2.1 From organic to chemical production systems	30
2.2.2 Environmental problems.....	31
2.2.3 Shift back to organic production - towards a sustainable agriculture	34
2.3 Recycling waste into nutrients.....	35
2.3.1 Integrating crop and animal production	35
2.3.2 Managing wastes through composting.....	36
2.4 Organic <i>vs.</i> conventional farming - economical aspects	38
2.5 A closer look at compost.....	40
2.5.1 Definition and process	40
2.5.2 Biological, chemical and physical properties	41
2.5.3 Effects on soil properties	42
2.5.3.1 Chemical aspects.....	43
2.5.3.2 Physical aspects.....	45

2.5.4 Effects on soil microorganisms biomass and activity	46
2.5.4.1 The role of soil microorganisms in soil fertility	46
2.5.4.2 Factors affecting soil microorganisms	48
2.5.5 Effects on plants.....	50
2.5.6 Effects on weed control	51
2.5.7 Practical considerations on the use of compost	52
2.5.7.1 Time of application.....	52
2.5.7.2 Method of application.....	53
2.5.7.3 Rates of application	53
Chapter 3. General Material and Methods	55
3.1 Maize cultivars.....	55
3.2 Treatments applied.....	55
3.2.1 Fresh Dairy Manure	55
3.2.2 Dairy Manure Compost.....	55
3.2.3 Nitram	56
3.3 Field experiments	56
3.3.1 Site, climate and soils.....	56
3.3.2 Experimental area.....	56
3.3.3 Seedbed preparation and drilling	57
3.3.4 Treatment application.....	57
3.3.4.1 Fresh Dairy Manure	57
3.3.4.2 Dairy Manure Compost.....	59
3.3.4.3 Nitram	59
3.3.5 Herbicide application.....	59
3.3.6 Sampling	60
3.3.6.1 Manure and Compost	60
3.3.6.2 Soil.....	60
3.3.6.3 Crop	61
3.3.6.4 Weeds	62
3.3.7 Harvest.....	62
3.4 Glasshouse experiments	64
3.4.1 Establishing the experiments.....	64
3.4.2 Assessing the experiments.....	65
3.5 Analysis of soil nutrients	65
3.5.1 Total Nitrogen.....	65
3.5.2 Ammonium- and Nitrate-N, extractable, in moist soil	66
3.5.3 Phosphorus, extractable	66
3.5.4 Potassium and Magnesium, extractable	66
3.5.5 Cation Exchange Capacity and exchangeable Calcium.....	66

3.5.6 Moisture Content (Dry Matter Content).....	67
3.5.7 Organic Matter Content	67
3.5.8 Soil pH.....	67
3.6 Analysis of soil microbial biomass and activity	67
3.6.1 Methods to estimate soil microbial biomass	67
3.6.2 Estimation of soil microbial activity	69
3.7 Analysis of plant material	69
3.7.1 Leaf Area Measurement	69
3.7.2 Plant nutrients.....	69
3.7.3 Digestibility of forage maize.....	69
3.8 Statistical analysis	70
Chapter 4. The 1993 Field Experiment.....	71
4.1 Effects of fresh and composted dairy manure on maize (<i>Zea mays</i> L.) nutrition, crop production and weed control.....	71
4.1.1 Introduction	71
4.1.1.1 Objectives.....	72
4.1.2 Material and methods.....	72
4.1.3 Results	77
4.1.3.1 Soil nutrient analyses	77
4.1.3.2 Soil biological assessments	79
4.1.3.3 Maize Destructive Growth Analyses	81
4.1.3.4 Maize harvest	82
4.1.3.5 Maize nutrient uptake.....	85
4.1.3.6 Weed analysis.....	87
4.1.3.7 Soil temperature.....	89
4.1.4 Discussion.....	89
4.1.5 Conclusions	94
Chapter 5. The 1994 Field Experiments	96
5.1 Field A - Effects of dairy manure compost on soil fertility, maize (<i>Zea mays</i> L.) production and weed growth.....	96
5.1.1 Introduction	96
5.1.1.1 Objectives.....	97
5.1.2 Material and methods.....	97
5.1.3 Results	100
5.1.3.1 Soil nutrient analyses	100
5.1.3.2 Soil biological assessments	103
5.1.3.3 Maize Destructive Growth Analyses	106
5.1.3.4 Maize harvest	107

5.1.3.5 Maize nutrient uptake.....	109
5.1.3.6 Weed analyses.....	109
5.1.4 Discussion.....	110
5.1.5 Conclusions	114
 5.2 Field B - Effects of dairy manure compost on soil fertility, maize (<i>Zea mays</i> L.) maturity and maize production.....	 118
5.2.1 Introduction	118
5.2.1.1 Objectives.....	118
5.2.2 Material and methods.....	118
5.2.3 Results	121
5.2.3.1 Soil nutrient analyses	121
5.2.3.2 Maize Destructive Growth Analyses.....	124
5.2.3.3 Maize harvest	125
5.2.3.4 Maize nutrient uptake.....	127
5.2.4 Discussion.....	129
5.2.5 Conclusions	131
 Chapter 6. The 1995 Field Experiments	133
6.1 Cumulative effects of dairy manure compost on soil fertility, maize (<i>Zea mays</i> L.) production and weed growth, with comparisons of results under different climatic conditions.....	 133
6.1.1 Introduction	133
6.1.1.1 Objectives.....	134
6.1.2 Material and methods.....	134
6.1.3 Results	138
6.1.3.1 Soil nutrient analyses	138
6.1.3.2 Soil biological assessments.....	143
6.1.3.3 Maize Destructive Growth Analyses.....	147
6.1.3.4 Maize harvest	148
6.1.3.5 Maize nutrient uptake.....	153
6.1.3.6 Weed analyses.....	155
6.1.4 Discussion.....	156
6.1.5 Conclusions	162
 Chapter 7. The Glasshouse Experiments	164
7.1 The 1993 Glasshouse Experiment - Effects of different rates of dairy manure compost on maize (<i>Zea mays</i> L.) nitrogen nutrition	 164
7.1.1 Introduction	164
7.1.1.1 Objectives.....	164

7.1.2 Material and methods.....	164
7.1.3 Results	166
7.1.4 Discussion.....	170
7.1.5 Conclusions	171
 7.2 The 1994 A Glasshouse Experiment - Effects of different rates of dairy manure compost on maize (<i>Zea mays</i> L.) nutrition	 173
7.2.1 Introduction	173
7.2.1.1 Objectives.....	173
7.2.2 Material and methods.....	173
7.2.3 Results.....	175
7.2.4 Discussion.....	178
7.2.5 Conclusions	179
 7.3 The 1994 B Glasshouse Experiment - The potential for weed infestation of dairy manure compost.....	 180
7.3.1 Introduction	180
7.3.1.1 Objectives.....	180
7.3.2 Material and methods.....	180
7.3.3 Results.....	181
7.3.4 Discussion.....	181
7.3.5 Conclusions	181
 7.4 The 1995 Glasshouse Experiment - Effects of dairy manure compost on soil water content under maize (<i>Zea mays</i> L.) production	 183
7.4.1 Introduction	183
7.4.1.1 Objectives.....	183
7.4.2 Material and methods.....	183
7.4.3 Results.....	185
7.4.4 Discussion.....	188
7.4.5 Conclusions	189
 Chapter 8. The 1995/96 Laboratory Experiment.....	 190
8.1 Nitrogen mineralisation rates of dairy manure compost applied to different soils under controlled conditions.....	 190
8.1.1 Introduction	190
8.1.1.1 Objectives of the laboratory experiment	190
8.1.1.2 Nitrogen transformation processes.....	190
8.1.2 Material and methods.....	191

8.1.3 Results	195
8.1.4 Discussion.....	198
8.1.5 Conclusions	201
Chapter 9. Comparison between Climatic Conditions in Experiments.....	202
9.1 Introduction.....	202
9.2 Temperature	202
9.2.1 Seasonal variations between field experiments	202
9.2.2 Relation between maize developmental stages and accumulated heat units.....	204
9.2.3 Comparisons between field, glasshouse, and laboratory conditions	204
9.3 Rainfall	207
9.3.1 Seasonal variations between field experiments	207
9.4 Photoperiod	208
9.4.1 Comparisons between field, glasshouse, and laboratory conditions	208
9.5 Discussion	208
Chapter 10. General Discussion and Conclusions	211
10.1 Introduction.....	211
10.2 General Discussion	211
10.2.1 Mineralisation of compost nitrogen	211
10.2.2 Compost effects on soil fertility and crop production	213
10.3 Recommendations for Future Research	222
10.4 Summary and Conclusions	222
References.....	225
Appendices	241
Appendix 1. Decimal code for maize developmental stages	241
Appendix 2. Results of soil analysis prior to treatment application.....	242
Appendix 3. Analyses of dairy manure compost, fresh dairy manure and peat compost prior to application in experiments	243
Appendix 4. Methods of soil chemical analyses	245
Appendix 5. Methods of analyses of plant material.....	248
Appendix 6. Analysis of soil microbial biomass and activity	250

Appendix 7. Weed species in field experiments, grouped by growth habit.....	252
Appendix 8. Weed score in the 1993 field experiment, classified by growth habit	253
Appendix 9. 1993-1995 meteorological data in Wye and Viterbo	254
Appendix 10. Other results of maize DGAs in field experiments	258

List of Tables

Table 2.1 Mineral composition of forage maize DM at maturity	29
Table 2.2 Total accumulation of nutrients at physiological maturity in above ground plant parts	29
Table 2.3 Chemical composition ranges of matured composts	41
Table 4.1 Additives used in 1993 field experiment	73
Table 4.2 Diary of operations in the 1993 field experiment	75
Table 4.3 Soil extractable P, K and Mg levels with atrazine application in the 1993 field experiment	77
Table 4.4 Carbon microbial biomass with and without atrazine application in the 1993 field experiment	79
Table 4.5 Nitrogen microbial biomass with and without atrazine application in the 1993 field experiment	80
Table 4.6 Microbial activity as metabolic quotient with and without atrazine application in the 1993 field experiment	81
Table 4.7 Maize leaf area index with and without atrazine application in the 1993 field experiment	81
Table 4.8 Maize dry matter production with and without atrazine application during the 1993 field experiment	82
Table 4.9 Maize total P, K, Ca and Mg uptake with and without atrazine application in the 1993 field experiment	86
Table 4.10 Weed total N, P, K, Ca and Mg uptake without atrazine application in the 1993 field experiment	87
Table 5.1 Treatments used in 1994 Field A experiment	98
Table 5.2 Diary of operations in the 1994 Field A experiment	99
Table 5.3 Soil extractable P, K and Mg levels in the 1994 Field A experiment	101
Table 5.4 Maize leaf area index in the 1994 Field A experiment	105
Table 5.5 Maize dry matter production in 1994 Field A experiment	107
Table 5.6 Maize total N, P, K, Ca and Mg uptake in the 1994 Field A experiment, in plots with weed control	109
Table 5.7 Weed dry biomass production in the 1994 Field A experiment, in plots without weed control	109
Table 5.8 Weed total N, P, K, Ca and Mg uptake in the 1994 Field A experiment, in plots without weed control	110
Table 5.9 Additives used in 1994 Field B experiment	119

Table 5.10 Diary of operations in the 1994 Field B experiment.....	120
Table 5.11 Soil total-N levels with forage maize cultivars <i>Aziz</i> and <i>LG2080</i> in the 1994 Field B experiment.....	122
Table 5.12 Soil NO ₃ -N levels with forage maize cultivars <i>Aziz</i> and <i>LG2080</i> in the 1994 Field B experiment.....	122
Table 5.13 Soil extractable K levels with forage maize cultivars <i>Aziz</i> and <i>LG2080</i> in the 1994 Field B experiment.....	123
Table 5.14 Soil extractable P and Mg levels with forage maize cultivars <i>Aziz</i> and <i>LG2080</i> in the 1994 Field B experiment.....	124
Table 5.15 Maize leaf area index with forage maize cultivars <i>Aziz</i> and <i>LG2080</i> in the 1994 Field B experiment.....	125
Table 5.16 Maize dry matter production with forage maize cultivars <i>Aziz</i> and <i>LG2080</i> in the 1994 Field B experiment	125
Table 5.17 Maize total P, K, Ca and Mg uptake with forage maize cultivars <i>Aziz</i> and <i>LG2080</i> in the 1994 Field B experiment.....	128
Table 6.1 Treatments used in the 1995 field experiments	135
Table 6.2 Diary of operations in the 1995 field experiments	136
Table 6.3 Soil total-N % in the 1995 <i>Field 1 year</i> and <i>2 years</i> experiments (Wye).....	138
Table 6.4 Soil extractable P levels in the 1995 <i>Field 1 year</i> and <i>2 years</i> experiments (Wye).....	141
Table 6.5 Soil extractable K levels in the 1995 <i>Field 1 year</i> and <i>2 years</i> experiments (Wye).....	142
Table 6.6 Soil extractable Mg levels in the 1995 <i>Field 1 year</i> and <i>2 years</i> experiments (Wye).....	142
Table 6.7 Maize dry biomass production in the 1995 <i>Field 1 year</i> and <i>2 years</i> experiments (Wye)	148
Table 6.8 Maize fresh biomass yield in the 1995 field experiments in Wye (<i>Field 1 year</i> and <i>2 years</i>) and in Viterbo.....	148
Table 6.9 Maize dry matter content in the 1995 field experiments in Wye (<i>Field 1 year</i> and <i>2 years</i>) and in Viterbo.....	150
Table 6.10 Cob expressed as % of dry matter and maize digestibility in the 1995 <i>Field 1 year</i> and <i>2 years</i> experiments (Wye)	152
Table 6.11 Maize total P, Ca and Mg uptake in the 1995 <i>Field 1 year</i> and <i>2 years</i> experiments (Wye)	153
Table 6.12 Weed dry biomass production in plots without weed control in the 1995 <i>Field 1 year</i> and <i>2 years</i> experiments (Wye).....	155
Table 6.13 Weed total N, P, K, Ca and Mg uptake in plots without weed control in the 1995 <i>Field 1 year</i> and <i>2 years</i> experiments (Wye)	155

Table 7.1 Treatments used in 1993 glasshouse experiment	165
Table 7.2 Maize P, K, Ca and Mg uptake at 45 and 60 days in the 1993 glasshouse experiment.....	169
Table 7.3 Treatments used in 1994 A glasshouse experiment	174
Table 7.4 Maize P, Ca and Mg uptake in the 1994 A glasshouse experiment.....	177
Table 7.5 Treatments used in the 1995 glasshouse experiment.....	184
Table 8.1 Characteristics of the soils used in laboratory experiment	192
Table 8.2 Treatments used in laboratory experiment	194
Table 9.1 Monthly maximum temperature means during the 1993-1995 field experiments in Wye and in Viterbo (1995 only).....	203
Table 9.2 Monthly total rainfall during the 1993-1995 field experiments in Wye and in Viterbo (1995 only).....	207

List of Figures

Figure 1.1 General objectives of this research project	22
Figure 2.1 Compost as a way of integrating crop and animal production	37
Figure 3.1 Scheme of maize and weed sampling in each plot	61
Figure 4.1 Layout of the 1993 field experiment.....	74
Figure 4.2 Soil total-N % with atrazine application in the 1993 field experiment	78
Figure 4.3 Soil nitrate levels with atrazine application in the 1993 field experiment	78
Figure 4.4 Maize fresh biomass yield with and without atrazine application in the 1993 field experiment.....	83
Figure 4.5 Maize dry matter yield with and without atrazine application in the 1993 field experiment.....	83
Figure 4.6 Maize total nitrogen uptake with and without atrazine application in the 1993 field experiment.....	88
Figure 4.7 Weed dry biomass production without atrazine application during the 1993 field experiment	88
Figure 5.1 Layout of the 1994 Field A experiment.....	98
Figure 5.2 Soil total-N % in the 1994 Field A experiment.....	101
Figure 5.3 Soil nitrate levels in the 1994 Field A experiment (raw data)	102
Figure 5.4 Soil nitrate levels in the 1994 Field A experiment (logarithmically transformed data).....	102
Figure 5.5 Carbon microbial biomass in the 1994 Field A experiment.....	104
Figure 5.6 Nitrogen microbial biomass in the 1994 Field A experiment.....	104
Figure 5.7 Microbial activity in the 1994 Field A experiment.....	105
Figure 5.8 Maize fresh biomass yield in the 1994 Field A experiment	108
Figure 5.9 Maize dry matter yield in the 1994 Field A experiment	108
Figure 5.10 Layout of the 1994 Field B experiment	120
Figure 5.11 Maize fresh biomass yield with forage maize cultivars <i>Aziz</i> and <i>LG2080</i> in the 1994 Field B experiment	126
Figure 5.12 Maize dry matter yield with forage maize cultivars <i>Aziz</i> and <i>LG2080</i> in the 1994 Field B experiment.....	126
Figure 5.13 Maize total nitrogen uptake with forage maize cultivars <i>Aziz</i> and <i>LG2080</i> in the 1994 Field B experiment	128
Figure 6.1 Layout of the 1995 field experiments.....	136

Figure 6.2 Soil nitrate levels in the 1995 <i>Field 1 year</i> experiment	140
Figure 6.3 Soil nitrate levels in the 1995 <i>Field 2 years</i> experiment	140
Figure 6.4 Carbon microbial biomass in the 1995 field experiment in Wye (<i>Field 2 years</i>)	144
Figure 6.5 Carbon microbial biomass in the 1995 field experiment in Viterbo	144
Figure 6.6 Nitrogen microbial biomass in the 1995 field experiment in Wye (<i>Field 2 years</i>)	145
Figure 6.7 Nitrogen microbial biomass in the 1995 field experiment in Viterbo	145
Figure 6.8 Microbial activity in the 1995 field experiment in Wye (<i>Field 2 years</i>)	146
Figure 6.9 Microbial activity in the 1995 field experiment in Viterbo	146
Figure 6.10 Maize dry matter yield in the 1995 <i>Field 1 year</i> and <i>2 years</i> experiments (Wye)	151
Figure 6.11 Maize dry matter yield in the 1995 field experiment in Viterbo	151
Figure 6.12 Maize total nitrogen uptake in the 1995 <i>Field 1 year</i> and <i>2</i> <i>years</i> experiments (Wye)	154
Figure 6.13 Maize total potassium uptake in the 1995 <i>Field 1 year</i> and <i>2</i> <i>years</i> experiments (Wye)	154
Figure 7.1 Maize dry matter production at 45 days from the experiment start (1993 glasshouse experiment)	167
Figure 7.2 Maize dry matter production at 60 days from the experiment start (1993 glasshouse experiment)	167
Figure 7.3 Nitrogen uptake by maize at 45 days in the 1993 glasshouse experiment	168
Figure 7.4 Nitrogen uptake by maize at 60 days in the 1993 glasshouse experiment	168
Figure 7.5 Maize dry matter production in the 1994 A glasshouse experiment	176
Figure 7.6 Nitrogen uptake by maize in the 1994 A glasshouse experiment	176
Figure 7.7 Potassium uptake by maize in the 1994 A glasshouse experiment	177
Figure 7.8 Maize fresh biomass production in the 1995 glasshouse experiment	186
Figure 7.9 Maize dry matter production in the 1995 glasshouse experiment	186

Figure 7.10 Interaction in maize fresh biomass production between physical effect and water regime in the 1995 glasshouse experiment	187
Figure 7.11 Interaction in maize dry matter production between physical effect and water regime in the 1995 glasshouse experiment	187
Figure 8.1 Net N mineralised at each sampling date from compost (NO ₃ -N as % of compost total N) applied to two soils (1995/96 laboratory experiment)	196
Figure 8.2 Cumulative net N mineralised from compost (NO ₃ -N as % of compost total N) applied to two soils (1995/96 laboratory experiment).....	196
Figure 8.3 Net N mineralised from compost (g NO ₃ -N.kg ⁻¹ fresh weight compost) applied to two soils, at each sampling date (1995/96 laboratory experiment)	197
Figure 8.4 Cumulative net N mineralised from compost (g NO ₃ -N.kg ⁻¹ fresh weight compost) applied to two soils (1995/96 laboratory experiment).....	197
Figure 9.1 Cumulative Ontario Units from maize drilling in the 1993-1995 field experiments in Wye.....	205
Figure 9.2 Cumulative Ontario Units in Wye from the start of the field and glasshouse and the laboratory experiments	205
Figure 9.3 General relationship between maize growth stages and accumulated effective temperature.....	206
Figure 9.4 Accumulated temperature from maize emergence in field and glasshouse experiments in Wye.....	206

List of Plates

Plate 3.1 Dairy manure and cereal straw being composted at the Controlled Composting Systems Unit.....	58
Plate 3.2 Spreading of compost prior to field experiments	58
Plate 3.3 Single-row forage maize harvester used in all field experiments	63
Plate 3.4 Harvested maize material being weighed in container	63
Plate 4.1 Maize development with weed competition in the 1993 field experiment.....	84
Plate 4.2 Maize development without weed competition in the 1993 field experiment.....	84
Plate 5.1 Inter-row brush weeder being used for mechanical weed control in the 1994 Field A experiment	116
Plate 5.2 Maize plots in the 1994 Field A experiment in July.....	116
Plate 5.3 Maize plots in the 1994 Field A experiment in September	117
Plate 5.4 Maize varieties <i>LG2080</i> and <i>Aziz</i> in a split plot design in the 1994 Field B experiment.....	117
Plate 6.1 Maize plots with and without weed control in the 1995 <i>Field 2 years</i> experiment.....	149
Plate 6.2 Compost-treated maize plots with 100 and 200 kg N.ha ⁻¹ in the 1995 <i>Field 2 years</i> experiment.....	149
Plate 7.1 Maize pots at 60 days in the 1993 glasshouse experiment prior to sampling	172
Plate 7.2 Layout of the 1994 A glasshouse experiment.....	172
Plate 7.3 Maize pots under drought conditions at the end of the 1995 glasshouse experiment.....	182
Plate 7.4 Maize pots under normal water regime at the end of the 1995 glasshouse experiment.....	182
Plate 8.1 Leaching tubes in the 1995/96 laboratory experiment	193
Plate 8.2 Vacuuming to remove excess solution from soil in leaching tubes in the 1995/96 laboratory experiment.....	193

Abbreviations and Symbols

ADAS	Agricultural Development and Advisory Service
BC	microbial Biomass Carbon
BN	microbial Biomass Nitrogen
CEC	Cation Exchange Capacity
DGA	Destructive Growth Analyses
DM	Dry Matter content
FE	Fumigation-Extraction method
FI	Fumigation-Incubation method
gds	grams of dry soil
GLM	General Linear Model
GS	maize Growth Stage
herb	herbicide
LAI	Leaf Area Index
MAFF	Ministry of Agriculture, Fisheries and Food
NCD	method of Neutral detergent/Cellulase Digestibility
NIAB	National Institute of Agricultural Botany
OM	Organic Matter content
OU	Ontario Units
$q\text{CO}_2$	chemical representation of metabolic quotient
RCB	Randomised Complete Block design
SED	Standard Error of the Difference
USDA	United States Department of Agriculture
WHC	Water Holding Capacity
+ and -	+ and - herbicide

Chapter 1. Introduction

1.1 General aspects

Maize (*Zea mays* L.) has been studied in this research project for a sustainable production system because of its importance as a cereal, both in tropical and temperate regions. It is an annual row crop, grown primarily for grain for both human and animal consumption (Fageria *et al* 1991). It can also be grown for sweet corn, green forage and silage. Forage maize gives high yields of dry matter per hectare, ensiling easily, with a high digestibility and energy value when compared to other forage crops (Wilkinson 1978).

Important maize producing countries are found worldwide, although climatic requirements limit growth to the warmer parts of the temperate regions and the humid subtropics (Fageria *et al* 1991). In the United States alone, maize is grown on about 24 million hectares (Magdoff 1991). In Brazil, it is the most widely grown crop, with 13.6 million ha in 1987 (Villachica *et al* 1990).

Grain yields of 10 t.ha⁻¹ and forage yields of 15-20 t DM.ha⁻¹ are common at a commercial level in temperate regions (Fischer and Palmer 1983; McConnell 1988). In the tropics, although these yields can be reached in experiments with good management practices, the average yield obtained by farmers is much lower, mainly due to nutritional deficits (Fageria *et al* 1991).

In temperate regions, maize is grown in intensive systems based on the use of external inputs such as inorganic fertilisers and herbicides. Dependence on oil makes inorganic fertiliser production expensive and unsustainable. Moreover, this is reflected in the high prices of the fertilisers. In the UK, these account for 15-20% of the cost of producing forage maize (Pain 1978). In tropical countries, maize is usually grown as a subsistence crop, and high cost agrochemicals are either unavailable or too costly for small farmers (Scholes *et al* 1994). Even when mineral fertilisers are applied, they have been unable to sustain soil fertility.

In fact, although increasing amounts of inorganic fertilisers are being used, decline in soil fertility is increasingly found worldwide, along with growing

environmental problems such as soil erosion and nitrate pollution of the ground water table (Stockle *et al* 1994). Furthermore, the unbalanced nutrient supply of chemical fertilisers has caused plants to become more susceptible to pest and disease attacks, intensifying the use of pesticides and fungicides (Edwards 1990), causing yet more actual or potential damage to the environment and to human health.

In Brazil, maize is mostly grown by small farmers, as livestock feed and a staple crop, with low average grain yields of around 1.8 t.ha⁻¹ (Villachica *et al* 1990). Farming systems are usually based on the use of chemical fertilisers, which due to high costs, are out of the reach of small farmers (Almeida 1991). Nevertheless, most of the farmers have livestock manure and crop residues available on the farm. These farm wastes can be used in a self-sustaining farming system to improve soil fertility, helping to achieve the full productive potential of the land.

Extensive investigation is being carried out in production systems of maize and other crops without the use of agrochemicals, but more research is needed to rationalise a production system with an adequate technology combining high yields with environmental conservation (Werner 1988). The effects of the use of compost in the soil-plant system need to be investigated, to ensure that it can be efficiently used as a fertiliser in a low-external-input production system (Sanchez *et al* 1989), either for maize or for other crops.

1.2 Objectives of this research

Based on the reality of small-holding maize production in Brazil, this research project aims to rationalise a sustainable production system for maize.

Accordingly, the use of compost derived from dairy manure and cereal straw, available on the farm, has been studied as an organic fertiliser for maize nutrition. These farm organic wastes are renewable resources, and their use increases the association of crop and animal production, thus recycling the nutrients at farm level. Hence, a low input and more sustainable production system for maize is attained.

The use of compost as organic fertiliser has further advantages as the enrichment of soil organic matter and enhancement of microbial size and activity, restoring and sustaining soil fertility. There are also positive effects on soil physical characteristics such as structure, making soil less susceptible to erosion (Dick and McCoy 1993). Moreover, using organic fertilisers instead of agrochemicals reduces the risks to the environment and to human health.

The general objectives of this research are to look at the use of dairy manure compost as a fertiliser for sustainable maize production, and at its effects on soil nutrient status and, ultimately, plant nutrition. Therefore, the effects of compost application on soil chemical and biological aspects (specifically soil nutrients and soil microbial biomass and activity), on maize nutrition and on maize and weed growth have been studied, examining the various interactions between soil and plants (Figure 1.1).

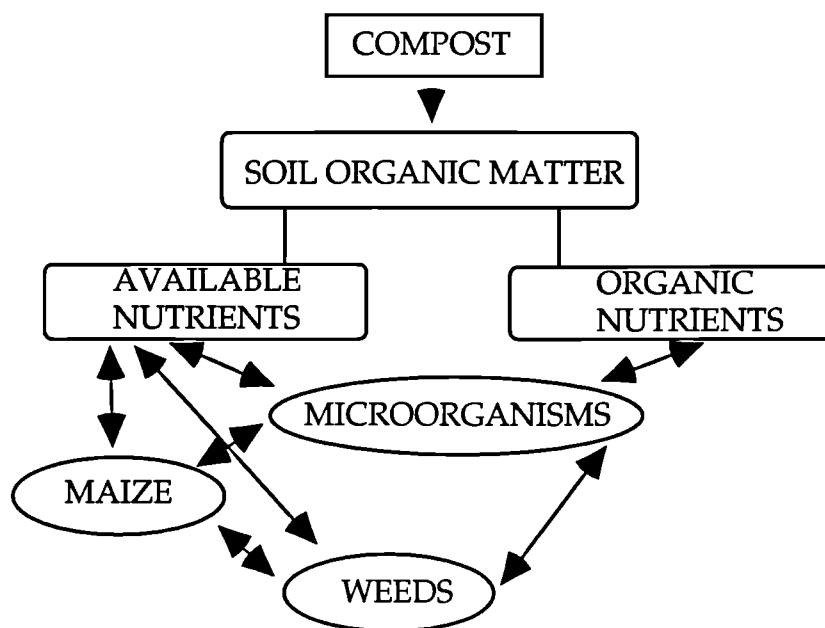


Figure 1.1 General objectives of this research project (single arrow indicates effects, double arrow indicates effects/interactions)

It is proposed that compost application can adequately supply maize nutrient requirements, by enhancing soil chemical and biological fertility, resulting in maize yields similar to the ones attainable with application of chemical fertilisers.

In addition, the application of compost is expected to result in lower soil nitrate levels than the one of inorganic fertilisers, thus associating compost with a lower pollution potential of the ground water table. These lower levels of soil available nitrogen along with compost physical effects are also expected to reflect in limited weed growth in compost-treated plots.

Most of the experiments have been conducted in Wye College Estate, UK, comparing the use of dairy manure compost and inorganic fertiliser in forage maize production. Both soil and crop nutritional status have been assessed, and crop and weed biomass production have also been monitored. A joint research project with *Università degli Studi della Tuscia*, in Viterbo, Italy, has allowed for a more detailed study of the soil biological fertility aspects.

Due to the importance of organic and low external input farming systems as a key to sustaining agriculture and environmental resources, it is believed that the results of this research are not only pertinent to small-holding maize production in Brazil. They are also relevant to other crops, either in a small or a large scale production, and to both tropical and temperate countries. The results, even if indirectly applied, can still provide a basis for future research in other regions and for other crops.

1.3 Structure of thesis

The relevant literature is reviewed in Chapter 2, looking at aspects of maize production (Section 2.1), characteristics of different production systems (Section 2.2), the possibility of recycling wastes into nutrients (Section 2.3), and a comparison of organic and conventional farming systems (Section 2.4). Section 2.5 looks specifically at compost, and its effects and interactions in the soil-plant system.

The general Material and Methods of all the experiments and the analyses done in this research are described in Chapter 3.

Field experiments carried out in Wye College Estate, UK, from 1993 to 1995 are presented in Chapters 4 to 6. Specific objectives, methodology and results are presented, with a brief discussion and conclusions of each experiment.

Chapter 4 describes the 1993 field experiment, which studied the use of fresh and composted dairy manure for maize nutrition, crop production and weed control. In Chapter 5, two field experiments conducted in 1994 are presented: Field A, looking at the effects of dairy manure compost on soil fertility, maize production and weed growth, and Field B, examining the results of compost application on soil fertility, maize maturity and maize production. Chapter 6 outlines the 1995 field experiments, which investigated the cumulative effects of dairy manure compost on soil fertility, maize production and weed growth. Additionally, a comparison is made of the experiments in Wye with a similar one in Viterbo, Italy, also undertaken in 1995.

Glasshouse experiments carried out from 1993 to 1995, looking at the use of compost in a controlled environment, are presented in Chapter 7. Section 7.1 describes the 1993 glasshouse experiment, which compared different rates of compost application for maize nutrition. Two experiments were conducted in 1994: Experiment A - effects of different rates of compost on maize nitrogen nutrition (Section 7.2), and Experiment B - the potential for weed infestation of dairy manure compost (Section 7.3). The 1995 glasshouse experiment is presented in Section 7.4, examining the effects of dairy manure compost on soil water content under maize production.

A laboratory experiment conducted in 1995/1996, studying nitrogen mineralisation rates of dairy manure compost applied to different soils under controlled conditions, is described in Chapter 8.

A summary of the different climatic conditions in all the field experiments is made in Chapter 9. Additionally, comparisons between the glasshouse, the laboratory and the field environments are presented, as well as a correlation between maize developmental stages and accumulated heat units.

A general discussion of the results obtained in all experiments, examining the nutrient dynamics from compost to crop, and the conclusions of this research project are presented in Chapter 10.

Chapter 2. Literature Review

2.1 Maize production

Maize (*Zea mays* L.) is the world's third most important cereal after wheat and rice. An annual row crop, it is grown primarily for grain, used for both human and animal consumption. It is also used for fodder and as raw material for industrial processes (Fageria *et al* 1991). Maize is important both in tropical and temperate regions, being grown in more countries than any other cereal, and producing the largest grain yield (per ha) of any cereal. Important producing countries include the United States, the former USSR, Romania, Italy, China, Brazil, Mexico, South Africa, India and Indonesia (Magdoff 1991).

2.1.1 Climatic requirements

Although widely distributed, maize is concentrated in the warmer parts of the temperate regions and in the humid subtropics, as it requires warm temperatures and adequate moisture. The optimum temperature for maize development is around 25-30°C, while below 10°C it ceases to grow. Rainfall during the growing season should be in the range of 460-600 mm in temperate areas, and 600-900 mm in the tropics. Maize also profits from high light intensity, being a C4 plant, with superior photosynthetic potential (Bunting 1978; Fageria *et al* 1991).

In the UK, only forage or silage maize can be grown, mostly confined to the south, as the climate is neither warm nor reliable enough for grain production. Late springs and cold short summers restrict both yield and dry matter content of forage maize. Growth stops with cold weather at the first sharp frost in autumn, and early sowing is impossible, as seeds fail to emerge in cold soil. Therefore, maize must be drilled as soon as soil temperature stabilises at 10°C, from late April to mid May, and it should reach harvest stage by late September to mid October (Bunting 1978; McConnell 1988).

2.1.2 Agronomic and physiological aspects

Maize grows on a wide range of soil types, but performs best on well-drained deep loam and silt loam soils, with adequate levels of organic matter and available nutrients, and with pH ranging from 6 to 8 (Bunting 1978; McConnell 1988).

A careful seedbed preparation is crucial for the good establishment of the crop. Maize requires a firm, fine seedbed, with a deep, well-aerated root bed. For maximum yields, maize density should be 110,000 plants.ha⁻¹, allowing 10% for losses after drilling. Seeds are drilled 5 cm deep, with 75 cm space between the rows. The interseed spacing is about 10 cm to achieve the optimum population (Bunting 1978; McConnell 1988).

Many plant characteristics and management practices depend upon the developmental stage of maize (Appendix 1), which itself is a function of temperature. Therefore, accumulated temperature is more suitable than calendar time to describe the phenology of maize (Bunting 1978; Groot *et al* 1986). The effective daily temperature will relate to the length of time in which the daily temperature is above the minimum required for maize growth and development. Accumulated effective temperature between maize developmental stages will be similar for different sites and seasons (Carr and Hough 1978), and can be used to predict stages of maturity or to identify suitable areas of production .

The May to October growing season is usually cooler in the UK than in other parts of North-Western Europe, on the basis of accumulated temperature. Therefore, early and medium early varieties must be chosen to ensure that the required degree of maturity is reached at harvest. The shoot dry matter (DM) content should then range from 20 to 30%, depending on site and season (Milbourn 1975; McConnell 1988).

Maize DM yield, DM content and content of grain increase with time, and maize digestibility is maintained at a high level during ripening. Therefore, for best quality as a forage, maize should be harvested only when maximum dry weight is reached, with dry matter content over 25%, to maximise the intake by animals (Bunting 1978).

2.1.3 Factors affecting maize productivity

Yields vary greatly between temperate, subtropical and tropical regions. In the UK, well grown crops of silage maize usually range from 11 to 14 t.ha⁻¹ of dry matter or from 52 to 62 t.ha⁻¹ of fresh material at 21% DM content, producing from 44 to 53 t.ha⁻¹ of silage (McConnell 1988). Grain yields of 10 t.ha⁻¹ are common in temperate regions at the commercial level, whereas yields over 20 t.ha⁻¹ have been reached under favourable conditions (Fischer and Palmer 1983).

In Brazil and other countries in the tropics, average grain yields of up to 9.5 t.ha⁻¹ can be reached in experiments with good management practices (Tsuji 1985). However, large differences occur between potential experimental yields and the ones obtained by farmers. Although it is the most widely grown crop in Brazil (13.6 million ha in 1987), maize has low average yields (1.8 t.ha⁻¹), mainly due to nutritional deficit (Villachica *et al* 1990). Maize is usually grown as a subsistence crop by small farmers, who have no access to improved management techniques. Low yields can be due to water and nutrient stresses, inadequate pest control, and use of poorly adapted cultivars with low yield potential (Fageria *et al* 1991). Farming systems based on the use of high cost chemical fertilisers are out of reach of small farmers (Almeida 1991).

Weed competition is also a major factor reducing maize yields. Weeds can easily develop in the wide inter-row spaces, and interfere with maize growth, particularly during the period of crop establishment, when maize has a relatively slow growth rate. The mean yield of weedy maize has been found to range from 32 to 80% of the yield of weed-free maize (van Heemst 1985).

In the UK there is limited attack by most of maize pests and diseases, as general climatic conditions are less favourable for their development, and they are unlikely to cause serious losses in yield. However, damage from low temperatures may occur at both ends of the growing season. At early stages, it can retard maize development, reflected in poorer yields (Cook 1978).

2.1.4 Nutrient requirements

Nitrogen (N) is the most important nutrient in determining the yield of maize, being essential for plant growth, as it is a constituent of all proteins. In favourable soil conditions for maize growth, ammonium N (NH_4^+) is rapidly converted to nitrate (NO_3^-) by nitrifying bacteria. Hence, although maize can absorb ammonium N, most N is taken up as nitrate (Pain 1978). N uptake is minimal at early stages of growth, increasing gradually to reach a maximum between start of flowering and early grain formation. A gradual decline in vegetative N occurs during reproductive growth stages, reflecting translocation to the developing grain. While the grain accounts for 40-60% of shoot dry matter, it contains 50-80% of the nitrogen in the shoot (Fageria *et al* 1991).

Phosphorus (P) is a constituent of cell nucleus, is essential for cell division, stimulates root formation in maize and aids crop maturity and grain development. It is taken up as orthophosphate (P_2O_5). An adequate supply is particularly important during early growth stages, when maximum accumulation occurs (Pain 1978). However, P accumulates steadily in maize until maturity, translocating from vegetative parts to the grain during grain fill (Fageria *et al* 1991). At maturity, the ear (female inflorescence containing the grains) accounts for 70% of the total P in plant (Pain 1978).

Potassium (K) is required by maize in large amounts, being necessary in all important physiological processes, and directly affecting rate of growth and yield of crop. Potassium has a specific effect on the opening of stomata, and a good supply is important for efficient use of light (photosynthesis) and water by maize. Most of the K (as K^+) in maize is taken up by silking, and tends to accumulate in stems, although it migrates from leaves to ears until maturity. Nonetheless, K has a considerable influence on the proportion of grain in the ear (Pain 1978; Mengel and Kirkby 1987; Fageria *et al* 1991).

Calcium (Ca) is important in the formation of cell walls, and tends to accumulate in the leaves. Magnesium (Mg) is part of the chlorophyll molecule, and inadequate supplies lead to reduction in photosynthesis. A high proportion of Mg migrates from leaves to the ears. Sulphur (S) is part of certain aminoacids, but maize has relatively low S requirements. Ca, Mg and S accumulate continuously in maize throughout the growing season. Sodium

(Na) does not seem to be essential for maize growth, although it passes freely through the roots, and tends to accumulate at the nodes (Pain 1978).

Micronutrients required by maize include iron (Fe), boron (B), zinc (Zn), copper (Cu), manganese (Mn), molybdenum (Mo) and chlorine (Cl). They are required in very small amounts, but are essential for plant growth (Pain 1978; Fageria *et al* 1991).

Table 2.1 Mineral composition of forage maize DM at maturity (Phipps 1977 in Pain 1978)

%	Stem	Leaf	Ear	Whole Crop
N	0.73	1.81	1.35	1.30
P	0.15	0.23	0.25	0.21
K	1.25	1.55	0.47	0.75
Ca	0.23	1.05	0.05	0.25
Mg	0.14	0.27	0.12	0.15
<i>ppm</i>				
Zn	24	33	26	26
Mn	13	35	8	14
Cu	3	8	3	4
Fe	75	191	95	100
Na	743	379	471	570

Nutrient uptake by maize is related to dry matter production. Estimates vary depending on yield levels and growing conditions (e.g. Table 2.2).

Table 2.2 Total accumulation of nutrients (kg.ha⁻¹) at physiological maturity in above ground plant parts. Yields are in t DM.ha⁻¹.

Country	Yield	N	P	K	Ca	Mg	Na	S	B	Cu	Zn	Mn	Fe
USA (1)	31.8	386	70	370	59	44	-	40	0.13	0.14	0.80	0.90	1.9
UK (2)	14.3	180	26	239	33	20	9	16	-	0.05	0.47	0.34	-

(1) Karlen *et al* 1988

(2) Phipps 1977 in Pain 1978

Forage maize has a high digestibility (72-75%) and energy value compared to other forage crops, due to its relatively high content of non-structural carbohydrates. Properly chopped maize ensiles easily, with a slight decrease

in digestibility (71-73%). The crude protein content ($N \times 6.25$) is usually 8-10% of the DM, changing little after ensiling (Wilkinson 1978).

In summary, maize requires large amounts of nutrients in order to reach its high yield potential. Moreover, as few residues are returned to soil, forage maize production results in loss of soil organic matter, further contributing to a lower soil fertility. Therefore, nutrients must be replaced in order to maintain soil productivity (Fageria *et al* 1991).

2.2 Historical background of production systems

2.2.1 From organic to chemical production systems

Organic inputs have been used throughout the centuries as soil conditioners and biofertilisers, proving an effective way of maintaining permanent and sustainable agriculture, in the Far East, Near East, Mexico, Peru and within the Greek and Roman Empires (Allison 1973; Parr and Hornick 1992). Until the middle of the 1900s, soil fertility was successfully maintained by crop rotation and the return of crop residues and animal manures to the land. This traditional production system was particularly suitable for low-resource farmers in developing countries, who could sustain agricultural productivity with a minimum of external inputs and costs (Parr and Hornick 1992).

However, after the Second World War, such agricultural practices in temperate regions were replaced by the use of chemical fertilisers and pesticides in the monoculture of maize, wheat and other cereal crops (Francis *et al* 1986). The new production system became a model in subtropical and tropical regions with the advent of the Green Revolution in the 1960s.

The world energy crisis in the early 1970s greatly increased the costs of chemical fertilisers and brought about uncertainty in their future availability, particularly in developing countries. It became clear that agricultural systems could not be based on an assured input of mineral fertilisers. Furthermore, many developing countries are unlikely even to effectively enter the fossil fuel era (Papendick and Elliott 1984; Francis *et al* 1986).

Moreover, increases in artificial fertiliser inputs, commonly based on maximum yield goals, have not been associated with corresponding increases in agricultural production. This is because mineral fertilisers do not supply all the nutrients required by the crops, particularly trace elements, and have no effects on physical and biological aspects of soil fertility (Dalzell *et al* 1987).

In Sweden, during 1980 the amounts of N and P applied were four times as high as the amounts ending up in agricultural food products (Jansson 1983 in Granstedt 1991). Reviews from maize experiments in the United States suggest that N application, since the mid-1960s, has exceeded crop requirements by 20-60% per year (Olson 1985), and that the grain recovery at maximum or economic optimum yields ranges only from 20 to 40% of the N fertiliser applied (Blackmer 1986; Oberle *et al* 1987 in Hallberg 1987).

These losses are even more substantial if it is considered that the production of fertilisers, primarily nitrogenous, requires nearly 30% of the total energy expended in US crop production (Pimentel *et al* 1984). In eastern Pennsylvania, a continuous high input maize production system requires more than twice as much total energy when compared with a low energy, non-chemical, biological structured system (Culik *et al* 1983 in Francis *et al* 1986). According to Papendick (1987), for every calorie of food produced in the United States, three calories are required in production.

Fewer comparisons have been made in tropical regions, but maize production in several countries shows a wide range of energy conversion efficiencies (units of energy produced per unit of energy invested), from 10-19 in human energy based systems to 3-4 in fossil fuel based ones (Heichel 1973 in Francis *et al* 1986).

2.2.2 Environmental problems

Despite the inefficiency of high input production systems, they are still profitable for the farmer in the short term, although the overproduction of certain crops in developed countries in recent years has resulted in lower commodity prices (Edwards 1990). Nevertheless, chemical fertiliser inputs have increased alarmingly, but they have been unable to sustain soil fertility.

In the long run, the excess applied represents not only a loss to farmers, but also a burden to the environment. Repeated applications of concentrated inorganic fertilisers are associated with soil degradation by erosion and the loss of soil productivity, which are now the most serious threats to agriculture worldwide (Parr *et al* 1984; Francis *et al* 1986; Parr and Hornick 1992; Stockle *et al* 1994).

Humanity depends on the ability of a limited area of land to provide most of its food, fuel and fibre needs to exist (Sanders 1992), but intensive agricultural practices lead to a decline in the useful lifetime of resources. At some point, the increasing yield reduction from erosion may exceed the diminishing increase due to technical progress (Reganold 1988; Lockeretz 1989). The USA alone may be losing as much as 6 billion tons of soil a year due to erosion (Napier 1986 in Sanders 1992).

Moreover, intensive agricultural practices can be harmful to the natural soil flora and toxic to the wildlife and to humans (Reganold 1988). Contamination of ground and surface water with synthetic fertilisers and pesticides is a common and growing problem worldwide (Lockeretz *et al* 1981; Papendick and Elliott 1984). Chemical nitrogen is of primary concern for ground water quality, as it is applied in large quantities to meet crop requirements. According to Hallberg (1987), many shallow ground water supplies now exceed recommended NO₃-N drinking water standards (11.3 mg.l⁻¹ in OECD nations, 10 mg.l⁻¹ in the United States), this being strongly associated with increases in the use of N fertilisers. Examples given are from England, France, Germany, United States, central Europe, the former USSR and New Zealand.

In the United States, as far as maize production is concerned, average N fertiliser rates increased from 72 kg.ha⁻¹ in 1965 to over 150 kg.ha⁻¹ in 1982 (Hargett and Berry 1983 in Hallberg 1987). Maize accounts for 21 percent of the cropland, but for 43 percent of the fertiliser nitrogen use. Not surprisingly, two major sustainability issues regarding maize N management are nitrate contamination of ground water and the large amount of fossil fuel used in production of N fertilisers (Magdoff 1991). Kohl *et al* (1971) estimated that a minimum of 55-60% of the nitrate found in the surface waters of an Illinois corn belt watershed originated from fertiliser nitrogen.

Soil nitrate is especially vulnerable to leaching after plants no longer utilize it (Maynard 1993). Following removal of maize in the autumn, with no transpiration and reduced evaporation due to cold weather, water will tend to percolate. Thus, any nitrate left in the soil will tend to leach mostly during the autumn, winter and early spring, eventually reaching the ground water. Nitrate content in the soil profile after the crop harvest can be an indication of its leaching potential (Magdoff 1991; Maynard 1993).

The intensive use of mineral fertilisers and pesticides has led to yet another environmental problem, that is the disposal of organic wastes and residues. In the United States, total annual production of both rural and urban wastes in 1977 was approximately 730 million dry metric tons (Parr and Hornick 1992), more than 90% of that consisting of crop residues (53.7%), animal manures (21.8%) and municipal solid waste (18.1%).

Indeed, in Western Europe and North America, the driving force for the use of organic waste in agriculture was the need for its disposal (Pratt *et al* 1973; Dick and McCoy 1993), following a sharp increase in confined animal production (Evans *et al* 1977; Xie and MacKenzie 1986; Sharpley and Smith 1995). This situation is pronounced in countries like Belgium, Holland and the UK (Vogtmann 1984). In England and Wales, it is estimated that 200 million tons of animal manure are produced annually, half generated by the dairy cattle industry (Bujang and Lopez-Real 1993), and proper management of these wastes is crucial. In some countries, animal husbandry is already limited and controlled by utilisation regulations (Chen and Inbar 1993).

Economic and environmental problems associated with higher chemical inputs and/or non use of organic inputs have occurred in developing countries as well. Under tropical conditions, the breakdown of organic matter is faster. Hence, with no regular inputs of organic fertilisers, many tropical soils have poor structures, are more susceptible to erosion, have a faster leaching of nitrogen and a greater degree of phosphorus fixation. The need for a new approach to soil management and fertilisation was dramatically stressed by recent drought and famine in the Sahel and Ethiopia (Dalzell *et al* 1987), caused by land degradation after years of intensive agriculture and soil erosion.

Moreover, the increased incidence of crop pests and diseases in tropical areas, associated with the use of chemical fertilisers, has led to a greater use of pesticides, causing yet more hazards to humans and to the environment (Edwards 1990).

2.2.3 Shift back to organic production - towards a sustainable agriculture

"Sustainable agriculture is one that, over the long-term, enhances environmental quality and the resource base on which agriculture depends, provides for basic human food and fibre needs, is economically viable, and enhances the quality of life of farmers and society as a whole" (Schaller 1990).

Continual agricultural research has indicated that the key to soil fertility and productivity is soil organic matter from adequate and regular additions of organic amendments such as crop residues, animal manures and green manures. These additions have beneficial effects for improving the chemical, physical and biological properties of agricultural soils (Allison 1973; Papendick and Elliott 1984; Parr and Hornick 1992).

Soil organic matter is composed of labile and humic fractions. The labile soil organic matter has rapidly mineralised components, with turnover rates ranging from a few days to a few years. It is very important in the maintenance of soil fertility as a source of plant nutrients due to its chemical and biological composition and rapid turnover. Humic substances are more recalcitrant components of soil organic matter, having very long turnover times. They are important to improve soil physical characteristics and cation retention (Woomer *et al* 1994).

Good organic input management in the long term helps improve or maintain soil structure, aiding water storage, drainage and root penetration. It increases soil microbial biomass, biological activity and earthworm population. It also improves soil fertility, with a higher labile fraction of soil organic matter, more uniform distribution of nutrients and higher ion exchange (Parr *et al* 1984; Vogtmann 1984; Francis *et al* 1986; Reganold 1988; Granstedt 1991; Magdoff 1991; Swift and Woomer 1993).

Surveys indicate that farmers have a desire to improve management practices and reduce chemical inputs (Lockeretz *et al* 1981; Hallberg 1987).

The accentuated dependence upon mineral fertilisers has led to a loss of technical knowledge of organic waste utilisation in many countries, making it necessary to reintroduce these techniques and to develop practices in accordance to modern technology (Parr *et al* 1984; Vogtmann 1984).

New approaches for medium and small sized farmers in developing countries are especially needed. They need to be consistent with their limited resources and their economic, social and political realities (OTA 1984 in Francis *et al* 1986; Smaling *et al* 1992). In many cases, mineral fertilisers are out of reach of these farmers, either because they are difficult to obtain, or too expensive to purchase.

Many of the soils in developing countries are low in organic matter and nutrient contents (Hornick and Parr 1987). The proper utilisation of on-farm sources of crop residues and manures to replace synthetic N fertiliser produced with high energy input is a desirable environmental, agronomic and economic practice.

2.3 Recycling waste into nutrients

2.3.1 Integrating crop and animal production

Livestock manure can be used to maintain soil fertility and physical stability (Baker and Raun 1989). At least 75% of ruminant livestock and nearly all poultry and swine are found on crop/livestock farms, animals being also a source of food and income for the farmers. About two-thirds of the world's domestic ruminants are found in the tropics (Raun *et al* 1982 in Baker and Raun 1989).

Sustainable systems should increase the association of crop and animal production (Baker and Raun 1989; Edwards 1990; Granstedt 1991). It reduces dependency on fossil-fuel based fertilisers, especially when we consider that 60-90% of the nutrients in animal feed ends up in manure and urine (Granstedt 1991). Such a production system is particularly consistent with the reality of farmers in developing countries. It makes for a more efficient use of production resources on the farm to improve and maintain soil fertility, developing more profitable and sustainable crop and animal production, with a better quality of life in the rural environment (Francis *et al* 1986, Swift and Woomeer 1993; van der Werf 1993).

Farm organic wastes can be recycled into excellent sources of nutrients for maize (Voss and Shrader 1984; Magdoff 1991; Luna *et al* 1994). Animal manure is an important source of nitrogen for agriculture. However, its application may sometimes result in high initial immobilisation of inorganic N in soil. Moreover, large amounts of N may be lost by NH₃ volatilisation after manure application (Sørensen and Jensen 1995), or by NO₃⁻ leaching. Cattle manure, for instance, although usually devoid of toxic pollutants, imposes major environmental problems such as odour and losses of nutrients due to leaching, when it is spread at high rates over agricultural land (Olsen *et al* 1970; Evans *et al* 1977; Miller and MacKenzie 1978; Hallberg 1987; Magdoff 1991; Chen and Inbar 1993; Maynard 1993, 1994a and b). This can also lead to the eutrophication of surrounding lakes and streams (Andersson 1986 in Granstedt 1991).

2.3.2 Managing wastes through composting

Composting has proved a useful tool for manure and other organic waste management (Chen and Inbar 1993). This ancient practice provides a more stabilised form of organic matter, minimising the losses of N occurring with the use of fresh animal manures. It keeps more of the nitrogen in the organic form, that resists leaching and is released slowly to the crop, helping to reduce environmental pollution. Furthermore, it causes minimal disruption of soil processes and enhances soil tilth, fertility and productivity (Parr *et al* 1984; Vogtmann 1984; Papendick *et al* 1987; Parr and Hornick 1992; Maynard 1994a and b).

There are other advantages in composting. By reaching temperatures of 55 to 60°C during the process, it kills most human, animal and plant pathogens. It also solves the problems of odours and weed seeds, and the storage and handling constraints of organic waste utilisation (Papendick and Elliott 1984; Parr *et al* 1984; Ott 1990; Dalzell *et al* 1987).

Moreover, soil management and the way nutrients are applied influence plant pests and diseases (Chaboussou 1980). Application of compost for soil fertilisation can minimise these problems by introducing beneficial microorganisms that are antagonistic to and competitive against soil-borne plant pathogens (Hornick 1992). Plants are also less susceptible to pest and disease attacks when receiving a balanced supply of macro and

micronutrients (Dalzell *et al* 1987), and this could be due to their lower water content and thicker cell wall.

Indeed, there is renewed interest in composting as a simple, relatively inexpensive, yet effective technology. It reduces costs for transportation of manures and increases farmers' self-reliance, with the on-farm nutrient cycling from crops to animals, then, through compost, back to fields. It is also flexible in allowing considerable trade-offs between labour and capital (Golueke 1972; Papendick and Elliott 1984; Francis *et al* 1986; Rynk 1994).

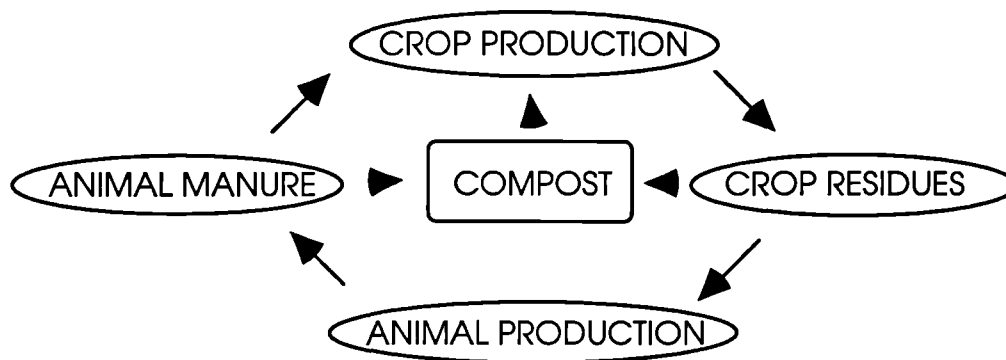


Figure 2.1 Compost as a way of integrating crop and animal production

This form of nutrient recycling increases soil organic matter while reducing soil erosion and nutrient runoff (Lockeretz 1988; Parr and Hornick 1992), following the basic concept of "feeding" the soil rather than the plant. Nutrients are moved from compost into the soil biomass and only after that into the soil water solution, to be absorbed by plants (Papendick and Elliott 1984). Compost thus maintains or improves soil capacity to supply nutrients to plants on a sustainable basis, and reduces nitrate leaching potential (Vogtmann 1984).

Experiments conducted by Maynard (1993, 1994a and b) showed that, after three consecutive years, nitrate concentrations in ground water remained below 10 ppm in plots amended with compost, applied at rates high enough to supply most of the nutrient requirements in an intensive vegetable production system, while they climbed to almost 15 ppm in plots treated with inorganic fertiliser.

2.4 Organic *vs.* conventional farming - economical aspects

Usually, people think of organic farms as small operations, but they can be as large as 600 ha in the United States (Elliott *et al* 1984). There are several thousand farmers running commercial farms in the US with little or no use of N fertiliser, relying exclusively on organic sources of N (USDA 1980). It is pertinent to add that, although composting was (and in most cases still is) essentially a small-scale batch operation, progress has been made in the understanding of the fundamental reaction and its application to large-scale and continuous waste treatment (Dalzell *et al* 1987).

The true value of organic materials as biofertilisers and soil conditioners is often misunderstood (Parr and Colacicco 1987). Commonly, their value is estimated by considering them as partial substitutes for chemical fertilisers. This is done by assessing the current market value of the plant nutrients they contain, especially the macronutrients (N, P, K). However, many organic materials contain other macronutrients and micronutrients that can contribute significantly to higher crop yield and quality (Allison 1973). Additionally, as they release N and P slowly, they have a greater residual effect on soil fertility than most chemical fertilisers. Hence, a significant proportion of the true value of organic inputs is in their ability to increase the yield of succeeding crops (Parr and Colacicco 1987).

Barbarika *et al* (1980 in Parr *et al* 1984) estimated that the cumulative economic value of some organic materials applied to agricultural soils could be as much as five times greater in succeeding years than the value realised during the application year. Moreover, the NPK monetary value of organic material is quite minor compared to its social and environmental benefits (Golueke 1972) and its positive effects on soil physical properties, which offers the best way to restore the productivity of eroded agricultural soils or to reclaim marginal soil (Hornick and Parr 1987). In tropical and subtropical environments, the major importance of compost application is indeed its ability to reduce soil erosion and to improve soil water retention (Dalzell *et al* 1987).

On average, yields range from higher to no more than 10% lower in non-chemical farming systems compared to conventional systems in temperate regions (Parr *et al* 1983). Maize production in the US Corn Belt, which usually receives heavy fertiliser and pesticide application, was about 8%

lower in organic farms when growing conditions were good, but yields from organic fields came closer to or even exceeded those of the conventional fields under poorer conditions (Lockeretz *et al* 1980, 1981). Sahs and Lesoing (1985) also reported higher yields for organically grown maize under heat and drought stress, compared to a conventionally grown crop. Hence, a sustainable farm is less vulnerable to price fluctuations, and yields are less variable from year to year (Lee 1992).

Besides, as far as yields and net returns are concerned, most comparisons of organic and low-input systems with conventional ones have a short-term approach, that can lead to erroneous conclusions. Although at first yields might be lower with the adoption of organic or low-input practices, they improve after a transition period, during which the soil ecosystem adjust to a new equilibrium (Doran *et al* 1987).

In long-term experiments, farmyard manure gave higher yields of small grain and root crops in England (Johnston and Mattingly 1976), and of maize in Colorado (Olsen 1986), when compared to those from chemical fertilisers. Reganold (1988) reported on long-term comparisons between one organic farm and an adjacent conventional farm in Washington, US. The organically farmed soil showed higher organic matter content, aggregate stability and water content, and higher levels of microbial activity and biomass, cation exchange capacity, pH, total N, extractable P and K, than the conventionally farmed one. It also had better structure and consistency for crop root growth and mechanical tillage, and thicker topsoil than the conventionally farmed soil, being more effective in maintaining soil productivity and reducing erosion rates. Although such unreplicated results should be treated with caution, similar results were found by Jordahl and Karlen (1993), when comparing conventional and alternative practices on adjacent farms in central Iowa, and on experimental results comparing manure and inorganic N as fertilisers (Dubetz *et al* 1975; Evans *et al* 1977; Sahs and Lesoing 1985; Xie and MacKenzie 1986; Eghball *et al* 1995; Sharpley and Smith 1995).

Chemical fertilisers have also been associated with problems in the maize crop itself. In the US Corn Belt, conventionally managed fields have shown twice as much lodging and *Diplodia* stalk rot as organically managed ones (Lockeretz *et al* 1980, 1981).

Adoption of production systems with reduced or no chemical use creates trade-offs among yields, production costs and net income at the farm level (Lee 1992). Due to their lower input costs, cropping systems with lower yields can still produce competitive returns (Chase and Duffy 1991). Production costs and energy inputs may be up to 40% lower in organic farms, although labour and management costs may be higher (USDA 1980). Pimentel *et al* (1984) reported that organic maize production in the US was 26-70% more energy efficient than conventional production, although the organic labour productivity ranged from 22 to 46% lower than conventional systems.

In developing countries, where employment in the rural area is needed, and with the work generally being carried out on a family basis, the higher labour requirement does not constitute a problem. In temperate regions, usually with high degree of mechanisation, the labour required on organic farms is only slightly higher than on conventional ones, in a still less energy intensive system (Lockeretz *et al* 1981; Vogtmann 1984; Lockeretz 1989). Additionally, less use of externally purchased inputs and higher dependence on resources of local origin, such as labour, has a beneficial community-level economic impact (Lockeretz 1989).

Furthermore, economic comparisons of organic and conventional agriculture production systems have failed to account explicitly for environmental damage (Faeth *et al* 1991 in Lee 1992). Potential improvements in human health and the environment from reduced chemical use must be weighed against effects on farm income and consumer food prices (Lee 1992). Additionally, total economic benefits from composting should be compared with the alternative disposal options for organic wastes, such as landfilling or incineration, in the case of municipal solid waste (Parr *et al* 1984).

2.5 A closer look at compost

2.5.1 Definition and process

According to Zucconi and de Bertoldi (1987), compost is the product of a controlled biooxidative process involving a solid heterogeneous organic substrate that passes through a thermophilic phase and a temporary release of phytotoxins. This leads to the production of CO₂, water, minerals and stabilised organic matter (the compost itself).

Controlled conditions distinguishes composting from natural rotting and anaerobically decomposition, which can occur in open dumps or manure heaps. Organic wastes can be composted in windrow piles, with frequent turning, or under forced aeration, and both methods ensure an adequate supply of oxygen to the heap. Temperature and moisture need to be monitored during the process (Kiehl 1985).

2.5.2 Biological, chemical and physical properties

Compost is considered mature when a low and stable level of microbial activity is reached, and organic matter is mainly in a humified form (Zucconi and de Bertoldi 1987). Compost ingredients and climatic conditions affect the period required for maturation. Towards maturity, the temperature of compost, O₂ consumption and C/N ratio decrease and level off. With increasing compost age, there is a decline in the rate of CO₂ evolution and organic C content. However, extractable humic substances, cation exchange capacity and NO₃⁻ levels increase until maturity is achieved. Reasonably mature compost is a brown-black crumbly material, with an earthy smell and a C/N ratio close to 10 (Chen and Inbar 1993).

Table 2.3 Chemical composition ranges of matured composts (Dalzell *et al* 1987)

Substance	Composition range (% dry weight)‡
Organic matter	25 to 80
Carbon	8 to 50
Nitrogen (as N)	0.4 to 3.5
Phosphorus (as P)	0.1 to 1.6
Potassium (as K)	0.4 to 1.6
Calcium (as Ca)	5.0 to 1.1
Ash (mineral matter)	75 to 20

‡ municipal waste composts have composition towards the left-hand column of figures, and farm/garden waste composts have it towards the right-hand column.

The chemical composition of the compost will depend on the organic wastes used in its preparation (Table 2.3). Farmyard manure consists of animal excreta and bedding material, which has crop residues (straw) and the remains of animal feed. Because bedding and livestock diets can vary in type and quantities, nutrient composition of manure also varies widely (Kiehl

1985; Lampkin 1990). Nevertheless, the proportions of nutrients in dairy farmyard manure are similar to those required by maize (Kiehl 1985), making it a good compost material for maize production.

Compost contains macro and micro nutrients in readily available or organic forms. When applied to the soil, microorganisms continue to degrade the humified organic matter, gradually releasing nutrients by mineralisation. It is difficult for authors to agree on indices of nutrient availability from organic manures, as they vary widely. Brinton (1985) and Brinton and Seekins (1994) estimated that 50-62% of the total N of fresh dairy manure was mineralised during the maize growing season, in contrast with only 15-20% for compost. Pratt *et al* (1973) suggested that 20 to 75% of the total N of cattle manure was mineralised during the first year of application, depending on its water and nitrogen content. Beauchamp (1983) found that the N availability of incorporated liquid cattle manure was 50-60% that of fertiliser N.

The mineralisation of N from composted manures added to soil depends on their N content, C/N ratio, degree of maturity, carbon degradability and soil clay content. Complex soil-compost interactions occur together with N mineralisation-immobilisation turnover, and it is not easy to explain N mineralisation rates (Hébert *et al* 1991).

In warmer climates, there is a more rapid and complete decomposition of the labile organic matter, as microbial-mediated processes are accelerated with increasing temperature and moisture. In temperate conditions, the mineralisation is slower, and a portion of the organic matter becomes stabilised as soil humus (Duxbury *et al* 1989; Dick and McCoy 1993). Based on calculations by Paul and Voroney (1983), N flux through microbial turnover was about ten times higher in a Brazilian soil, compared to temperate soils in England and Canada.

2.5.3 Effects on soil properties

Soil quality may be defined as the capacity of a soil to function within ecosystem boundaries, to sustain biological productivity over the long-term, maintain environmental quality and promote plant, animal and human health (Parr *et al* 1992; Doran & Parkin 1994).

Many factors can reduce soil quality, such as erosion, nutrient runoff and leaching, loss of organic matter, crusting, compaction, desertification, and accumulation of toxic substances from excessive use of chemical fertilisers and pesticides. Organic matter plays a key role to offset many of these degradation processes (Parr *et al* 1992).

Compost application to soil can enhance soil quality due to its effects on soil chemical, physical and biological properties. Only chemical and physical aspects are reviewed in detail in this section. As far as biological aspects are concerned, addition of organic fertilisers has positive effects on micro and macroorganisms, such as the earthworms. These have a major influence on soil structure, fertility, aeration and drainage, and they can also enhance microbial activity, being therefore a key component on the soil ecosystem (Edwards 1980). Nevertheless, this study concentrates on microbial biomass and activity, which are reviewed in section 2.5.4.

2.5.3.1 *Chemical aspects*

Well stabilised composts increase soil organic C, soluble P and total N levels (Fraser *et al* 1988; Suzuki *et al* 1990; Giusquiani *et al* 1995). Maynard (1994a), reporting on soil nutritional status after three consecutive years of compost application, showed that total N was 6 times that of the control soil, and organic matter content had risen from 3.3 to 6.8%. Fraser *et al* (1988) reported on lower soil organic N and potentially mineralisable N levels under continuous cropping to corn and in non-manured compared to manured soils. Ott (1990) found that farmyard manure compost significantly increased soil organic matter and total N levels, during five years of application, in comparison to control and mineral N fertiliser.

With a low C/N ratio, compost rapidly releases plant available N. There is also evidence that it increases the rate of mineralisation of native soil N, P and K (Dalzell *et al* 1987). This can be explained by the "priming action", where the addition of organic inputs to soil stimulate the decomposition of native organic matter already present in the soil (Oberländer 1973). The priming action, however, does not lead to net losses of organic matter in the system, as part of the added organic matter will enter in the soil biomass in successive microbial generations, and part will be stabilised in the soil in humified form. Brinton (1985) suggested that, with continued organic

treatment, a point may be reached where adequate N is supplied each year from the usually 2-5% decomposition rate of soil organic matter.

Much of the phosphorus remains in the inorganic form during composting, and its availability depends on fixation reactions rather than mineralisation processes. Phosphate does not move easily in soil, and is precipitated in forms which cannot be absorbed by maize. Long term manure application was reported to increase the total soil P and the P availability to crops (Sharpley and Smith 1995; Tran and N'dayegamiye 1995). Tran and N'dayegamiye (1995) found a correlated average increase of 30% of P uptake by forage maize due to dairy manure application. Similarly, available phosphorus in soil was increased up to 57% with compost application, resulting in higher P uptake by maize (Mazur *et al* 1983a). The highly weathered soils of the tropics usually have lower total P content than in temperate regions, accentuating the importance of its supply to plant growth (Duxbury *et al* 1989).

Most soils contain large amounts of potassium, but it is released in a form available to plants at a very slow rate. Therefore, at any one time, only a small part of K will be in the soil solution. Maize has high demand for K. Dairy manure is particularly rich in this nutrient, with 4 kg $K_2O.t^{-1}$ (Pain 1978), hence dairy manure compost supplies available K in large quantities to maize.

In British clay and silt soils, exchangeable magnesium is often sufficient for crop requirements. Exchangeable calcium is present in large quantities in most temperate soils. Amounts of sulphur can be variable, but usually enough for maize requirements. Little information is available on micronutrient levels. In general, soils contain only small quantities of micronutrients, although sufficient for crop needs (Pain 1978). However, micronutrient deficiencies can occur, particularly in alkaline soils, due to fixation in unavailable forms. Compost application supplies macro and micronutrients, and deficiencies are less likely to occur (Pain 1978).

Soil reaction, or pH, largely determines the type of crop which can be grown on it. Most composts tend to have a neutral or slightly alkaline pH, and their application can help to modify extreme soil pH levels, or buffer the soil at a more favourable pH (Mazur *et al* 1983b; Tester 1990). In acid soils,

application of compost increases pH levels, with higher Ca and Mg contents (Kiehl 1985).

Addition of compost generally increases the cation exchange capacity (CEC), and thus both the ability of the soil to hold added mineral elements and the subsequent plant uptake of these elements (Epstein *et al* 1976).

2.5.3.2 *Physical aspects*

The value of organic inputs as soil conditioners may far outweigh their value as nutrient sources (Sanchez *et al* 1989).

Compost application has very beneficial effects upon soil physical properties. Addition of organic matter binds soil particles into crumbs, increasing soil aggregate stability and improving soil structure and porosity (Dick and McCoy 1993). In particular, there is an increase in the number of elongated pores. These pores are directly related to plant growth, favouring root penetration, storage of water and gases, and biological and biochemical activities important to soil fertility (Giusquiani *et al* 1995). The increased porosity results in decreased bulk density. With better soil structure conditions, the risks of erosion and crust formation are reduced (Kiehl 1985; Dalzell *et al* 1987; Tester 1990).

Moreover, compost addition results in higher soil water holding capacity and infiltration, due to both its capacity to absorb water (5 to 6 times its own weight) and its improvement of the soil pore system (Kiehl 1985; Dalzell *et al* 1987; Metzger and Yaron 1987). There is reduced evaporation, reduced nutrient runoff and increased plant available water, which can be crucial to plant development in dry weather conditions. Also, adequate moisture conditions are essential to ensure nutrient supply in the soil solution, affecting ultimately the ability of plants to absorb the nutrients (Pain 1978).

Additionally, compost application acts as a buffer in relation to soil temperature, helping to prevent extreme variations which can harm seed germination and plant development (Dalzell *et al* 1987).

2.5.4 Effects on soil microorganisms biomass and activity

2.5.4.1 *The role of soil microorganisms in soil fertility*

Soil microbial biomass consists of all soil organisms with less than about $5 \times 10^3 \mu\text{m}^3$ (including fungi, bacteria, actinomycetes, yeasts, protozoa), other than living plant material. It is the living component of soil organic matter, constituting about 1-3% of its total (Theng *et al* 1989).

Soil microorganisms are essential for the cycling of organic matter and nutrients in natural and agricultural soils, acting as a source and a sink for most plant-available nutrients (Jenkinson and Ladd 1981; Visser and Parkinson 1992). They decompose plant and animal residues, resulting in organic matter stabilisation, with positive effects on soil physical aspects, such as porosity and water retention (Doran *et al* 1987). Through the soil biomass the nutrients in organic soil fractions are made continuously available to plants (Brussaard *et al* 1993). Microorganisms also store carbon (C) and mineral elements such as N, P, K and Mg in their own living biomass (Anderson and Domsch 1980; Díaz-Raviña *et al* 1993).

Generally, according to Smith and Paul (1990), microbial biomass C (BC) accounts for 2-5% of total organic C; microbial biomass N (BN) represents 1-6% of total soil N, and microbial biomass P accounts for around 2.5-20% of soil organic P. The biomass has a much shorter turnover time (about 1.5-2 years in temperate soils) than total soil organic matter, in which turnover of some fractions may take thousands of years (Jenkinson and Ladd 1981). Therefore, this rapid turnover plays a major role in soil energy flow and as potential nutrient source for plants (Schnürer *et al* 1985; Wardle *et al* 1993).

It has been suggested that about 1 to 3 % of the total soil N is made available to crop plants each year through microbial mineralisation. The N in a single generation of microbial biomass could supply many crops with much of the N they require (Anderson and Domsch 1980; Fraser *et al* 1988). Similarly, substantial quantities of other nutrients are temporarily held in the biomass. In agricultural systems, crop demand for nutrients occurs during defined time intervals, and, when crops are absent, there may be nutrient losses by leaching and volatilisation (Duxbury *et al* 1989). Microbial immobilisation and mineralisation occur simultaneously in soils, and are important in recycling soil nutrients, storing them and making them available during

crop growth. With correct management of timing and placement of organic inputs, the efficiency of nutrient use by microorganisms and plants could be optimised (Doran *et al* 1987; Sanchez *et al* 1989; Buchanan and King 1992; Hendrix *et al* 1992).

Being an important labile pool of C, N, P and S, fluctuations in the size of soil microbial biomass and activity can influence soil fertility and crop productivity (Buchanan and King 1992). Waksman (1927) had already considered quantitative methods for studying microorganisms as indicators of the actual or potential fertility of soils. Soil biological processes in several areas have been used as indexes of soil fertility, such as carbon cycling (organic matter decomposition rate, soil respiration and microbial C biomass), nitrogen cycling and soil enzymes (Visser and Parkinson 1992). The size of microbial biomass is not always related to its activity, and there are a range of situations from high biomass with low turnover to low biomass with high turnover (Theng *et al* 1989).

Soil microbial biomass responds much faster to changes in the input of organic material into soil than does total soil organic matter, acting as a sensitive indicator of the side-effects of agricultural management practices. Changes in biomass can indicate trends in soil total organic matter content that could otherwise only be detected over a much longer period. Monitoring the status of soil biota and the functioning of the soil ecosystem provides information in assessing the sustainability of agricultural systems (Weil *et al* 1993). Powlson *et al* (1987) reported on experiments with straw incorporation over 18 years, where a very small increase in total organic C and N contents of soil occurred. However, proportional increases in biomass C and N were much greater. Such increases in biomass are more easily and accurately measured than are increases in total organic C and N, which have to be measured against a large background of C and N already present in soil.

The C/N ratio of the soil biomass can range between 3 to 12, depending on whether it is dominated by bacteria or fungi, respectively (Theng *et al* 1989; Wardle 1992). Total soil organic matter has a C/N ratio around 10-13 in agricultural soils (Duxbury *et al* 1989). Organic inputs with C/N ratio less than 20 generally have quick rates of decomposition and mineralisation of N, whereas those with higher ratios decompose slowly and can immobilise N (Sanchez *et al* 1989).

2.5.4.2 Factors affecting soil microorganisms

Microbial communities evolving from soil systems with heterogeneous inputs of organic matter will have more efficient production of biomass (Anderson and Domsch 1989). Addition of organic fertilisers not only adds microbial life to soil but they also act as a food source, stimulating the soil's own microbial biomass and activity to a greater degree than do mineral fertiliser inputs. This can be explained mainly by the easily available C, which is limited in soil under normal conditions, but also by the presence of N and other nutrients, and the improvement of soil physical characteristics, such as water content and resistance to erosion (Fraser *et al* 1988; Anderson and Domsch 1989; Wardle 1992). Furthermore, the microbial biomass is sustained for a longer period of time due to the slow release of nutrients, and the reduced nitrogen leaching (Wardle 1992). Microbial biomass C, N, P and S were significantly increased over a 12 month period in a compost-treated soil (Perucci 1990). Inorganic N applications have no direct effect on soil organic matter, measured as total soil organic C, and cause varied responses in soil biota, from stimulation to induced reductions of size and activity (Wardle 1992). Although N fertiliser application can cause a rapid, transient increase in BN, it does not affect BC, indicating that BC is a better index of biological change than BN (Fauci and Dick 1994a).

Natural 'stresses' such as drought and freezing can reduce microbial activity by 50 percent or more (Visser and Parkinson 1992). Increasing temperatures between 20° and 35°C increase both microbial and plant root activity, these reaching a maximum when about 60% of the soil pore space is water-filled (Doran *et al* 1987). In an experiment, soil drying destroyed 1/4 to 1/3 of the microbial biomass, although it progressively returned to its original size after re-hydration (Bottner 1985). Organic inputs act as a buffer, maintaining soil water content and temperature relatively constant. With no addition of organic inputs, the regenerating biomass tended to be less active with each drying-wetting cycle (Buchanan and King 1992).

Wardle (1992) reported that the amount of soil microbial biomass depends on soil texture and structure. It is lower in sandy soils than in clay soils, under similar management. The organic matter in clay soils has a longer turnover time, leading to accumulation of microbial biomass, whereas in sandy soils the potential C for mineralisation is much higher (Hébert *et al* 1991). According to Wardle (1992), there is a significant positive relationship

with aggregate size and stability, hence a higher microbial biomass in grassland compared to arable systems. Soil pH is also considered to be an important factor in influencing the proportion of soil organic C and N immobilised in the microbial biomass.

Furthermore, soil microorganisms are affected by the crop. They are fewer and less active under conventional cash grain systems, as compared to grain/forage or grain/legume rotations. A direct relationship has been demonstrated between the size of soil microbial biomass and both plant growth and rooting activity (Lynch and Panting 1980; Carter and Rennie 1984). Activity of microorganisms is largely confined to the rhizosphere, which continually supplies available C and N to the soil system (Theng *et al* 1989; Smith and Paul 1990; Wardle 1992). Reduced plant cover decreases species diversity in soil microbial communities (Visser and Parkinson 1992). Soil amendments can influence microbial biomass indirectly, with the return of more plant residues to soil resulting from improved plant nutrition (Insam *et al* 1991).

Results from studies of side-effects of agrochemicals on soil microorganisms show a great range of sensitivity. In the short-term, most pesticides and fertilisers, at recommended application rates, do not seem to significantly impact total microbial population measurements such as biomass and general activity. However, certain populations of algae, bacteria, fungi and actinomycetes have shown medium to high sensitivity to agrochemicals. Moreover, soil respiration, denitrification, ammonification, organic matter degradation rate and nitrification were also moderately to highly affected by the use of mineral fertilisers and pesticides (Visser and Parkinson 1992). Nevertheless, Fauci and Dick (1994b) found that long-term inorganic N applications decreased organic matter and biological activity, but long-term manure application showed significantly higher microbial biomass C and N and soil enzyme activities.

Wardle *et al* (1993), reporting on the response of soil microbial biomass and plant litter decomposition to weed management strategies in maize, found no consistent direct effects of applied herbicides (including application of atrazine). However, there can be indirect effects on microbial biomass and activity caused by the reduced plant cover following herbicide application (Wardle 1992).

Microbial biomass is influenced by seasonal changes, due to changes in soil moisture and temperature, and, indirectly, to the influence in plant growth. These changes are important to regulate microbial turnover, and thus nutrient availability and plant nutrition. Warmer climates also lead to faster turnover of microbial biomass, having lower microbial BC levels than temperate or cool temperate areas (Wardle 1992).

Insam *et al* (1991) demonstrated that green or farmyard manure increased the BC:organic C ratio on soil, and that this ratio was positively correlated with crop yields. Moreover, a greater microbial population increases the potential for nutrient cycling. A large amount of N is stored in the relatively labile microbial biomass (Jenkinson and Ladd 1981). This reserve of biological N can bring direct benefit to grain crop production, or can conserve N in a form less susceptible to loss by leaching or denitrification (Fraser *et al* 1988). Hence, on-farm recycling of organic materials for crop production is desirable to achieve a proper balance between soil organic matter, soil biota and crop productivity (Schnürer *et al* 1985; Doran *et al* 1987).

2.5.5 Effects on plants

Doran *et al* (1987) reported that, during a transition period from conventional to organic farming system, nitrogen deficiency symptoms and lower maize grain yields were observed in the latter. This was associated with lower N-NO₃ levels in soil and a greater proportion of N held in the weed biomass and soil microbial biomass. Generally, if a sufficiently mature compost is applied, N deficiency due to microbial competition does not occur. Suzuki *et al* (1990) reported the results of a 60 year experiment in Japan, comparing the effects of continuous application of inorganic fertiliser and compost on rice yields, with equal annual additions of N. Yields were lower in compost-treated plots during the first ten years, but recovered, and after 30 years the compost plots produced higher rice yields. Moreover, after 20 years, plant nitrogen uptake was greater in the compost- compared to the inorganic fertiliser-treated soil.

In the plant-soil system, there can be an interaction between root cells and humic acids, if humic molecules in the soil solution are small enough to flow in the apoplast and reach the plasma membrane. Varanini *et al* (1993) found results indicating a direct effect of low molecular weight (LMW) humic

substances on K⁺-stimulated ATPase activity of plasma membrane vesicles isolated from oat roots. Results also indicated that LMW humic substances are particularly active in stimulating ion uptake in root tissues, with an increase in passive membrane permeability to protons, and a specific action on transmembrane NO₃⁻ fluxes. These results show the importance of components of humified soil organic matter in the complex interactions between plant and soil. They might also explain the stimulatory effect of soil humic substances on plant nutrition and growth.

Compost application can enhance the quality of plant foods as well. Vogtmann *et al* (1993) reported on improved storage performance and superior sensory quality (taste) of tomatoes with compost application, compared to the use of mineral fertilisers. Vegetables produced with mineral fertiliser had higher nitrate (which may lead to cancer) and lower vitamin C levels than the ones with compost. Furthermore, application of mineral fertilisers may increase the dry matter yield and total protein content, but not necessarily the protein quality. Rendig (1984) showed that the ratio of essential aminoacids (those that the human body cannot synthesise) to non-essential aminoacids decreased for barley, wheat and rye under mineral N application, hence lowering protein quality. There is an increasing awareness over the use of agrochemicals in food crops (Hornick 1992). Compost as fertiliser meets the consumers' growing demand for healthy, uncontaminated foods (Clancy 1986).

2.5.6 Effects on weed control

Weed competition is a major factor lowering yields in organic systems (Doran *et al* 1987), and forage maize is highly sensitive to it. Chemical fertilisers have been associated with increased weed growth (Moomaw 1987 in Edwards 1990). Compost seems to affect weed growth to some extent and, hence, weed control practices.

Applying large quantities of compost as a mulch, i.e. leaving it on soil surface, can help in suppressing weed growth (Lal 1974; Dalzell *et al* 1987). Schmalzle (1990) found that the use of compost between the rows in vegetable production helped to suppress weed growth. Titov and Babakov (1988) reported that seeds of 12 weeds species had reduced or suppressed germination in the presence of compost or semi-liquid manure. Ligneau and Watt (1995) found that domestic compost reduced weed emergence,

particularly of species with small seeds. This was due mainly to the physical effect, and, to a lesser extent, to the chemical effect of compost. Large seeds were unaffected, suggesting that compost as a mulch could help to control weeds in cereals (Lee *et al* 1992; Ligneau and Watt 1995).

In the UK, the herbicide atrazine (2 chloro-4[ethylamino]-6[isopropylamino]-s-triazine) was widely adopted as a method of weed control in maize. It is a cheap residual herbicide that controls many broad leaved and grass weeds (Ivens 1994; Morrish and Lee 1994), but maize is not susceptible to it.

A further effect of dairy manure compost on weed control would be its influence in herbicide mineralisation. Entry and Emmingham (1995) reported that application of dairy manure to pasture soils significantly increased degradation of atrazine and 2,4-D (2,4-dichlorophenoxyacetic acid) in all seasons of the year, whereas inorganic N application inhibited their mineralisation. However, both organic and inorganic treatments increased active fungal and bacterial biomass. The results suggest that only the organic treatment increased the number of microbial species able to degrade the herbicides, and/or the activity of exo-enzymes responsible for this degradation. Similarly, Chopra and Magu (1985a and b) reported on several studies where compost additions counteracted the toxic effects of linuron and atrazine application on wheat and maize growth.

2.5.7 Practical considerations on the use of compost

2.5.7.1 Time of application

It is not easy to determine the optimum time of compost application. Considering a stabilised compost, maximum fertiliser benefit can be obtained with application as close as possible to the time of crop establishment, ensuring availability of soluble nutrients for crop uptake. In temperate climates, application in spring would be more beneficial in this aspect than in autumn (Dalzell *et al* 1987; Tester 1989).

In contrast, enhancement of soil physical properties due to compost application are longer lasting. Tester (1990) observed significant physical changes in soil up to five years after compost application at rates as low as 60 t.ha⁻¹.

2.5.7.2 Method of application

Compost can be left on the surface as a mulch, or incorporated into the soil at various depths. Whether one method or the other is more beneficial depends on the rate of application, soil type, climate and topography.

Incorporation is recommended when low rates of compost are applied, to allow a more even distribution in the field. Some authors suggest organic matter breakdown can be reduced by deep incorporation, resulting in longer lasting benefits and in greater crop productivity under certain climate conditions (e.g. Dick and McCoy 1993). In contrast, Sanchez *et al* (1989) affirms that decomposition is generally faster for incorporated than surface-applied material.

Higher rates left on surface may provide benefits as a mulch, improving soil moisture storage and decreasing evaporation losses for short periods of drought (Lal 1974), and providing better conditions for soil microbial activity (Wardle *et al* 1993). However, it can reduce plant growth in extremely dry conditions, as much of the water will be held in the compost mulch layer (Dick and McCoy 1993). Furthermore, the mulch itself will tend to dry out, reducing its microbial activity under these conditions.

Maize is sensitive to extreme soil temperatures at early stages of growth. Mulching can diminish daily temperature fluctuations on soil, being recommended in case of great disparity between minimum and maximum soil temperature (Lal 1974). It also lowers the temperature maxima in hot conditions and raises the minima in cold conditions (Lal 1987).

Surface application provides a direct benefit in reducing water runoff and erosion, and in preventing the formation of crusts by raindrop impact on soil (Jakobsen 1988; Ballif 1989-1990).

2.5.7.3 Rates of application

Additions of compost to soil are generally in rates ranging from 25 to 100 t.ha⁻¹, although greater variation can occur. These rates aim to provide optimum nutrient levels for crop development without causing environmental problems, such as excessive NO₃-N levels resulting in its leaching to groundwater. Higher application rates may result in

degeneration of soil physical conditions, with an excessively wet soil (Tester 1990).

Several studies have suggested that adding both inorganic fertilisers and composts together can have a synergistic effect on crop yield, combining the immediately available nutrients of the former with the longer supply and chemical, physical and biological advantages of the latter (Pain *et al* 1977; Dick and McCoy 1993). It has been recommended that each source, organic and inorganic, should supply at least 30% of the N (Dalzell *et al* 1987).

Chapter 3. General Material and Methods

3.1 Maize cultivars

Forage maize cultivar *LG2080* (hybrid) was used in most glasshouse and field experiments (Chapters 4-7), being recommended by NIAB (1993) for general use in the south of England. It has average dry matter (DM) yields (12.5 t.ha^{-1}) of high DM content at harvest (38%), with early maturity, moderate early vigour, moderate to good resistance to lodging, and an average height of 192 cm.

An earlier cultivar of forage maize, *Aziz* (hybrid), was also used in one field experiment of 1994 (Chapter 5), to look at the possible effect of compost on maize maturity. *Aziz* is provisionally recommended for special use in areas with a short growing season (NIAB 1994). It has DM yields of 13.7 t.ha^{-1} , high DM content at harvest (40.5%), very early maturity, good early vigour, moderate resistance to lodging and an average height of 203 cm.

3.2 Treatments applied

3.2.1 Fresh Dairy Manure

Manure consisted of fresh dairy excreta mixed with cereal straw, which had been used as bedding material. It was applied as a treatment (chemical composition in Appendix 3) in the 1993 field experiment (Chapter 4), and also used as a raw material for the production of compost (Section 3.2.2).

3.2.2 Dairy Manure Compost

Compost used in all experiments (Chapters 4-8) was produced once a year in the Controlled Composting Systems Unit (CCS), at Wye College, University of London. Fresh dairy manure (Section 3.2.1) was piled in covered bays (Plate 3.1), being turned every 1-2 weeks, to ensure aerobic conditions. High temperatures (60°C) were reached during the process, and the compost took an average of 3-4 months to mature. The final product had a brown-black colour, reasonably crumbly texture, although occasionally wet, with a C/N ratio close to 10 (further details in Appendix 3).

3.2.3 Nitram

Nitram is a highly soluble inorganic N fertiliser, composed of ammonium nitrate, containing 34.5% of total N. It was therefore assumed that all Nitram applied would rapidly become available.

3.3 Field experiments (Chapters 4-6)

3.3.1 Site, climate and soils

Experiments were conducted in *Orchard Field*, on Wye College Estate, University of London, Kent, UK (51°N, 1°E, altitude of 40-50 m above sea level). The climate is typical for South-Eastern England, being relatively warm and dry by British standards. Mean annual rainfall at Wye from 1963 to 1992 was 719 mm. For the agro-climatic region, between 1941 and 1970, mean annual potential evapotranspiration was 532 mm, and monthly air temperature means were 11.5, 14.5, 16.3, 16.2, 14.5, and 11.4°C from May to October, respectively (MAFF 1984).

Soil was of the Coombe series (Soil Survey of England and Wales in Green and Fordham 1973), with a moderately deep phase, a brown calcareous silt loam (USDA classification in Avery 1990), containing 22.6% clay, 56.8% silt and 20.6% sand. It had a pH of 8.0, and a high organic matter content (4.5%). Further details in Appendix 2.

3.3.2 Experimental area

Field experiments had either a randomised complete block design (RCB) or a split-plot design in randomised blocks (Mead and Curnow 1983). In the split-plot design, treatment factors are considered as main-plots, or further divided into subplots, depending on their relative importance in the analysis. Four replicates (blocks) were used for every treatment in all field experiments. Plots (on RCB, or subplots on split-plot) were 48 m², being 3 m wide and 16 m long. Each plot (in this chapter the word includes subplot) had four rows of maize, spaced at intervals of 0.75 m. The two outer rows were discarded, and data were collected from the two inner rows only.

Inter-block areas and a 10 m-wide strip around the experiments were also drilled with maize for block protection, as a wind-break, and to decrease any edge effect in the plots. Tracks (2 m wide) were left between the blocks for access.

3.3.3 Seedbed preparation and drilling

Careful seed bed preparation is essential to ensure good establishment of forage maize crops in the initial stages of development, and hence final dry matter yields (Bunting 1978). Soil was ploughed in early spring to a 20-30 cm depth and power-harrowed (10-15 cm depth) to incorporate applications of compost or manure (as applicable). Forage maize was drilled at the rate of 120,000 seeds.ha⁻¹, at 5 cm depth. After drilling, the soil was rolled, to reduce the risk of seeds been eaten by birds.

3.3.4 Treatment application

Treatments were compared as nutrient suppliers to soil and crop. The only limiting nutrient for maize production, based on previous soil analysis (Appendix 2) was nitrogen. Accordingly, all treatments were applied at rates equivalent in terms of their N availability for maize during its growing season. Two rates of application were used for each treatment in all experiments, either supplying 50 and 100 or 100 and 200 kg N.ha⁻¹.

3.3.4.1 *Fresh Dairy Manure*

Manure, applied before drilling, was spread uniformly on the surface with a JF spreader, and incorporated into soil by power harrow (10-15 cm depth). This treatment was used only in the 1993 field experiment (Chapter 4).

Manure was applied so that it was approximately equivalent to Nitram and compost in terms of plant nitrogen availability. Brinton (1985) estimated that 50-60% of total N in manure was made available during a maize growing season. Xie and Mackenzie (1986) estimated that 40% of total manure N was mineralised in field conditions. Castellanos and Pratt (1981) estimated that manure N availability was twice that of compost. The rates of manure application were based on these estimates, assuming a 50% N mineralisation rate, and applying manure at half the rates of compost application.



Plate 3.1 Dairy manure and cereal straw being composted at the Controlled Composting Systems Unit (temperature monitored by thermometer).



Plate 3.2 Spreading of compost prior to field experiments (spreader designed by technicians at Wye College Agricultural Engineering Workshop).

3.3.4.2 Dairy Manure Compost

Compost was either incorporated into soil or left on the surface as a mulch. In the case of incorporation, it was first uniformly spread on the surface with a compost spreader created by technicians at the Wye College Agricultural Engineering Workshop (Plate 3.2), and then incorporated into soil by power-harrow (10-15 cm depth). When applied as a mulch, it was evenly spread on the surface immediately after drilling (Chapter 4).

The rates of application were calculated so that compost would be approximately equivalent to Nitram in terms of nitrogen availability to maize. In a maize experiment, Brinton (1985) estimated that 20% of total N in compost was released during the growing season, and this mineralisation rate was used as a basis for calculation of the amounts of compost applied.

3.3.4.3 Nitram

All Nitram was applied at one stage, around maize emergence, as a top dressing. This had to be done before maize had 2 leaves unfolded (Growth Stage GS 1.50, Groot *et al* 1986, Appendix 1) to avoid fertiliser granules being trapped inside the leaves, damaging maize plants.

3.3.5 Herbicide application

Herbicide was used in field experiments, to compare the effects of compost application on the soil-plant system with and without the presence of weeds. Atrazine (2-chloro-4[ethylamino]-6[isopropylamino]-s-triazine) is a residual triazine herbicide which offers good control of many broad-leaved and grass weeds, without damaging maize at the recommended application rates (Bunting 1978). It was used in most field experiments, applied as Gesaprim 500 SC from Ciba-Geigy (3.4 litres dissolved in 200 litres of water.ha⁻¹), soon after crop emergence. Application was done when the soil was wet, or immediately before rain, for best results.

Clopyralid is a foliar, translocated picolinic herbicide that controls some broad-leaved weeds in maize (Ivens 1994). It was used in the 1994 Field A experiment (Chapter 5), applied as Dow Shield from DowElanco (0.5 litres in 250 litres of water.ha⁻¹), at the young weed seedling stage (maize at GS 1.75, 2-3 leaves, Groot *et al* 1986, Appendix 1), in dry soil, for best results.

An inter-row brush-weeder and a hoe for mechanical weed control were used in the same 1994 Field A experiment (Chapter 5), as clopyralid failed to control weeds. Manual weeding with a hoe was also done in the maize rows.

3.3.6 Sampling

3.3.6.1 *Manure and Compost*

Prior to application in soil, several samples were taken from the manure piles, at different depths and from different places, evenly mixed together and sent to ADAS Wolverhampton (500 g) for chemical analysis (Appendix 3). The same procedure was carried out for the compost. From the results of the analyses, the amounts of manure and compost to be applied were calculated, as detailed in Sections 3.3.4.1 and 3.3.4.2 above.

3.3.6.2 *Soil*

Soil samples were taken before treatment application in all field experiments, for the initial soil nutrient status (Appendix 2), and at several stages of maize development, to monitor the chemical and biological fertility of the soil before, during and after the period of crop demand for nutrients.

Six samples were taken at random from each block before treatment application, and four samples were taken at random from every plot after treatments were applied. Samples were taken with an auger (0-20 cm depth), evenly mixed together and sub-sampled for nutrient analysis. The soil was sieved to a 2-mm mesh. A small portion (40 g) of the fresh sub-sample was kept at 4°C for nitrate, ammonium and DM determination. The rest (200 g) was air-dried and stored at room temperature for further determinations (total-N, extractable P, K, Ca, Mg, OM, pH, CEC), as described in Section 3.5.

For the analyses of microbial biomass and activity (Section 3.6), samples were taken as above, but only from three blocks. After coarse-sieving, fresh samples (200 g) were stored in plastic bottles with sufficient aeration at 4°C until analysis (24-48 hours), carried out in Wye College in 1993 (Chapter 4). In 1994 and 1995 (Chapters 5 and 6), samples were sent in plastic bottles at 4°C by Express Courier Service (48 hours) to *Università degli Studi della Tuscia*, in Viterbo, Italy, where they were analysed by the Department of Agrobiological and Agrochemistry.

3.3.6.3 Crop

Destructive Growth Analyses (DGAs) were done at several stages of crop development. Maize samples (the whole plant was cut immediately above ground) were taken from two quadrats of 0.25 m² (1 m wide X 0.25 m long) placed over the two inner rows, one at each end of each plot (Figure 3.1). Thus, a total of 0.5 m² was sampled per plot, in an average of 8-10 maize plants, which were placed together in large labelled plastic bags and taken to a cold room (4°C) to await measurements and analyses. At the first sample, quadrats were placed 1 m in from each end of the plot, to avoid edge effect. In subsequent DGAs, quadrats were placed with 0.5 m distance from the previous sample. Quadrats were placed this way for more representative and uniform samples. As maize is drilled in widely spaced rows, simply placing quadrats at random would result in a large variation in the number of plants per quadrat. Germination pattern, disease and pest occurrence and symptoms of nutrient deficiency or toxicity were also observed.

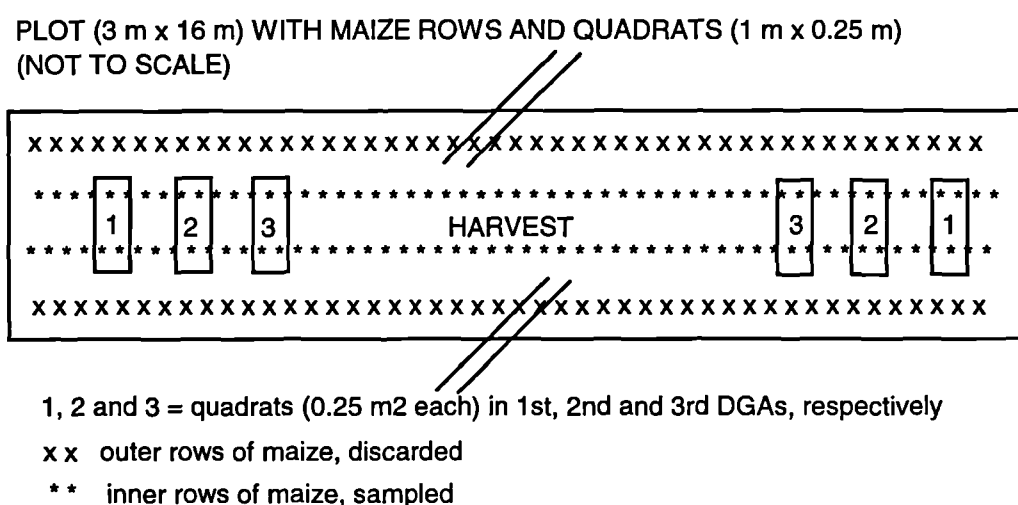


Figure 3.1 Scheme of maize and weed sampling (DGAs) in each plot.

For fresh biomass determination, all maize plants per bag were weighed, then only four plants per bag were kept (at random), the others being discarded. In some experiments, plant height and diameter of stem were determined for these four plants with an average being calculated per plot. Maximum plant height was measured, with leaves being pulled upwards along the stem. Stem diameter was measured at the bottom first internode. These same four plants were weighed fresh and split into leaves, stems with

the tassel (male inflorescence), and ears/cobs, depending on the stage of crop development. The fresh weight of all leaves was recorded, and approximately one fifth was re-weighed and used for leaf area index determination (Section 3.7.1).

Afterwards, all leaves, stems with tassel, and cobs from the 4 plants per plot were put in three separate labelled paper bags, and dried in the oven at 80°C for 120 hours. The dry matter weight of all maize parts was determined separately. The parts were then ground together (per plot) to 1 mm-mesh in a stainless steel mill, and stored in plastic bags at ambient conditions for N, P, K, Ca and Mg analyses (Section 3.7.2). If there were large quantities of ground material, a sub-sample of 20 g per plot was taken.

3.3.6.4 *Weeds*

Weed samples were also taken in DGAs, where applicable, simultaneously with maize sampling (Figure 3.1). The whole quadrat area was sampled for the above ground weed plants, only from weeds which were rooted inside the quadrat. Weed plants were placed in the same labelled plastic bags as maize, hence also stored at 4°C before being processed.

In initial DGAs in the field experiments, plants were split into grass and broad-leaved weeds, with horizontal or erect growing habit and with species identification (Appendix 7). For dry weight determination, all weeds per plot were put in labelled paper bags in the oven at 80°C for 72 hours, and the whole content of each bag was weighed. The dry weeds per bag were ground together through a 1 mm-mesh, and a subsample (20 g) was taken for N, P, K, Ca and Mg analyses (Section 3.7.2).

3.3.7 Harvest

Prior to maize harvesting, both ends of the plots were mown, so that only the central 10 m-long section of each row was left. As in the DGAs, only the two inner rows were considered, the two outer rows being discarded during harvest (Figure 3.1). A single-row forage maize harvester was used (Plate 3.3). Maize plants were chopped during harvesting, and collected in a metal container attached to a scale (Plate 3.4). The total weight per row was recorded with results from the two inner rows per plot being added.



Plate 3.3 Single-row forage maize harvester used in all field experiments. Maize plants in rows were chopped and collected in a container (Plate 3.4).



Plate 3.4 Harvested maize material being weighed in container (attached yellow box is the scale display). Samples were then collected for analysis.

A sample of approximately 500 g of fresh material was taken from each plot (a uniform mixture of the chopped maize from each of the two rows harvested). It was weighed fresh, then placed in labelled paper bags in the oven at 65°C for a week, for dry matter determination. The contents of each bag were ground through a 1 mm-mesh, sub-sampled (50 g) and stored in labelled plastic bags at ambient conditions for nutrient (N, P, K, Ca and Mg) and digestibility determinations (Sections 3.7.2 and 3.7.3, respectively).

3.4 Glasshouse experiments (Chapter 7)

3.4.1 Establishing the experiments

The glasshouse had an average temperature of 24°C during day and 17°C at night. Photosynthetically active incoming solar radiation was reduced by between 30% (overcast day) and 20% (clear day) inside the glasshouse compared with outside because of the glass (light readings taken at midday). The experimental design and number of replications varied in each experiment (Chapter 7).

Peat compost - 4:1 peat:grit (v/v), with no added fertiliser (P. Kite, pers. comm.) was used as a substrate and mixed with dairy manure compost or chemical fertilisers where applicable. Dairy manure compost and peat compost were sampled prior to the start of each experiment (as in Section 3.3.6.1) and sent to ADAS for analyses of their nutrient composition (Appendix 3). Dairy manure compost was applied at equivalent rates, in terms of N availability, to Nitram. As in the field experiments (Section 3.3.4.2), that was calculated based on Brinton's (1985) estimate that 20% of compost total N was mineralised during a maize growing season. The fertiliser rates used in glasshouse experiments were equivalent to those used in field experiments.

Pots of 7.5 litres volume (24 cm diameter x 20 cm height) were filled with the substrate mixture. Four seeds of forage maize (cultivar *LG2080*) were placed in each pot, and were thinned to three seedlings shortly after emergence. Each pot was placed in a saucer, to avoid loss of water and nutrients. The pots were watered on demand, unless drought conditions were being studied. Weeds were removed by hand as they germinated, to avoid competition with maize plants. A row of pots, each with one maize plant,

was placed around the experiment as a border for protection, being discarded from any measurement.

3.4.2 Assessing the experiments

Plant height and leaf area were determined on the glasshouse experiment of 1993. Height of the three maize plants per pot was measured once a week (on the tallest outstretched leaf), an average being calculated per pot. The leaf area was measured at the end of the experiment, from the tallest plant per pot (Section 3.7.1). Final shoot fresh and dry matter production were assessed in all experiments. The three maize plants per pot were cut immediately above ground, put together in a large labelled plastic bag and taken to a cold room (4°C) to await measurements. The fresh weight of the three plants per pot was determined shortly afterwards. The three plants per pot were then chopped, put together in a large paper bag, dried in an oven (65°C) for 120 hours and weighed for dry matter. Both fresh and dry matter production were calculated per pot (total of three plants).

When nutrient analyses were carried out, dry plants were ground through a 1 mm-mesh and stored in labelled plastic bags at ambient conditions to await N, P, K, Ca and Mg determinations (Section 3.7.2).

Germination pattern, disease and pest occurrence and symptoms of nutrient deficiency or toxicity were also observed in all glasshouse experiments.

3.5 Analysis of soil nutrients (detailed methods in Appendix 4)

3.5.1 Total Nitrogen

A Kjeldahl digestion was used, where organic matter in air-dried soil is decomposed by sulphuric acid, ultimately converting the nitrogen to ammonia, forming ammonium hydrogen sulphate in the digestion mixture. The process was accelerated by the use of a catalyst (selenium) and high digestion temperature. The content of nitrogen was then determined with a Burkard SFA2 auto-analyser by the Berthelot reaction, a colorimetric method in which ammonium salts react with alkaline sodium salicylate and sodium hypochlorite to form a bluish-green indophenol colour (Berthelot 1859).

3.5.2 Ammonium- and Nitrate-Nitrogen, extractable, in moist soil

Ammonium-, nitrate- and nitrite-nitrogen were extracted from moist soil with 2 M potassium chloride (MAFF 1986), and determined by an auto-analyser. $\text{NH}_4\text{-N}$ was determined by the Berthelot reaction (Section 3.5.1). Nitrite initially present in the sample was determined colorimetrically as the red dye formed by coupling diazotised sulphanilic acid with N-1-naphthylethylenediamine dihydrochloride (NEDD). Nitrate was quantitatively reduced by hydrazine sulphate to nitrite which was determined colorimetrically by the same diazotization-coupling reaction. Initial nitrite level was subtracted from the nitrate figure to give the true nitrate value (Kamphake *et al* 1967).

3.5.3 Phosphorus, extractable

Phosphorus was extracted from air-dried soil at $20 \pm 1^\circ\text{C}$ with sodium bicarbonate solution of pH 8.5 (MAFF 1986). Phosphate was determined by the Molybdenum Blue Method (Allen 1989). This method was based on the formation of a heteropoly-acid complex (phosphomolybdic acid) when an acid molybdate reagent is added to a solution containing orthophosphate. Reduction of the complex with stannous chloride gave the characteristic blue colour. The time period was critical for optimum colour development, which was measured spectrophotometrically.

3.5.4 Potassium and Magnesium, extractable

Potassium and magnesium were extracted from air-dried soil with M ammonium nitrate (MAFF 1986). The concentration of potassium in the extract was determined by flame photometry, significant interference by other elements did not occur. Magnesium concentration was determined by atomic absorption spectrometry, with the use of lanthanum chloride as a releasing agent.

3.5.5 Cation Exchange Capacity (CEC) and exchangeable Calcium

Soil was leached with M ammonium acetate which replaces the exchangeable cations (MAFF 1986). Excess ammonium acetate was removed from the soil with ethanol. The ammonium acetate extract was examined for exchangeable cations: calcium was determined by atomic absorption

spectrometry, using lanthanum chloride as a releasing agent. The leached soil was then extracted with potassium chloride which replaces the ammonium ions. This extract was analysed colorimetrically for ammonium ions to determine the CEC of the soil.

3.5.6 Moisture Content (Dry Matter Content)

The dry matter content of moist soil was determined by weighing out the soil samples into crucibles, and placing them in an oven at 105°C for at least 24 hours. Crucibles with soil were then cooled in a desiccator and re-weighed. The percentages of moisture and oven-dry soil were calculated from the loss in weight (MAFF 1986).

3.5.7 Organic Matter Content

Soil organic matter content was determined by loss-on-ignition (Ball 1964). Organic matter was burned off in a slow low-temperature ignition to avoid loss of inorganic soil material such as clay minerals and carbonates. By weighing the samples before and after ignition, the loss-on-ignition could be used as a measure of the soil organic matter content.

3.5.8 Soil pH

Soil hydrogen-ion activity (pH) was measured in 1:2.5 soil/water (v/v) suspension, with a calibrated pH meter (MAFF 1986).

3.6 Analysis of soil microbial biomass and activity (details in Appendix 6)

3.6.1 Methods to estimate soil microbial biomass

The chloroform (CHCl_3) fumigation-incubation method (FI) by Jenkinson and Powlson (1976) was used to estimate soil microbial biomass C (BC) in 1993 (Chapter 4). Soil is fumigated with CHCl_3 vapour, CHCl_3 is removed and the soil is then incubated for ten days. The biomass is calculated from the flush of decomposition (F_c), which is the difference between the amounts of CO_2 -C evolved during incubation by fumigated and unfumigated soil. Thus, $\text{BC} = F_c/k_c$, where k_c is the fraction of the biomass C mineralised to CO_2 over the incubated period, a value of 0.45 being commonly used for BC

calculations (Jenkinson and Ladd 1981). It is assumed that the extra CO₂ released after the soil fumigation and incubation comes from the cells of microorganisms killed by fumigation and decomposed by recolonising microorganisms (Stevenson *et al* 1989).

A variant (Shen *et al* 1984) was used to estimate soil microbial biomass N (BN) in 1993, calculated from the size of the flush of mineral N caused by fumigation. $BN = F_n/k_n$, where F_n is the difference between the amount of N released by incubation of fumigated and unfumigated soils, and k_n is the fraction of the biomass N that is released to soluble forms during incubation. Shen *et al* (1984) recommends a value for k_n of 0.68, although this can vary.

The FI is intended for use with well drained soils with relatively low organic matter content. Methodological problems such as choice of control, and the time of incubation limit the use of this technique, when routine analysis of many samples is required (Kaiser *et al* 1992). It also requires an optimum soil water content between 40-60% WHC, and is affected by soil dryness.

In 1994 and 1995 (Chapters 5 and 6), the CHCl₃ fumigation-extraction (FE) technique was considered more appropriate, and used to estimate BN (Brookes *et al* 1985) and BC (Vance *et al* 1987). The basis for the FE method is that the amounts of organic C and N in extracts of CHCl₃-fumigated soils are reasonably well-correlated with the corresponding amounts released to CO₂ or soluble N forms by incubation. In each case, the reagent used for extraction is 0.5 M K₂SO₄. The amount of N (E_n) or C (E_c) extractable after a 24 h CHCl₃-fumigation was calculated from the difference between total N or organic C in K₂SO₄ extracts from fumigated and non-fumigated soils. Hence, $BN = E_n/0.54$ (Brookes *et al* 1985), and $BC = 2.64 E_c$ (Vance *et al* 1987).

The FE method avoids the problem of choice of control in the FI method, and is applicable to water-logged soils and over the whole range of soil pH (Jenkinson 1988). There is no need for prolonged incubation of the soil and, for BN determination, errors do not arise due to denitrification and immobilisation of inorganic N during incubation (Stevenson *et al* 1989). The FE method is also recommended to soils which have recently received a substrate. In this case, during the incubation phase of FI, the potential for N immobilisation by the recolonising microbial population would result in an unreliable estimate of BN (Carter 1991).

3.6.2 Estimation of soil microbial activity

The microbial activity was expressed by its metabolic quotient ($q\text{CO}_2$), that is the microbial respiration:biomass ratio, measured from the data derived from BC estimates (Section 3.6.1). The metabolic quotient is the amount of $\text{CO}_2\text{-C}$ produced per hour per unit of microbial biomass carbon (Anderson and Domsch 1985).

Thus, $q\text{CO}_2 = \text{CO}_2\text{-C from non-fumigated soil.h}^{-1}.\text{BC}^{-1}$.

3.7 Analysis of plant material

3.7.1 Leaf Area Measurement

An Area Measurement System (ΔT - Delta-T Devices Ltd., Cambridge) was used for maize leaf area determination. Maize leaves were gripped and flattened by a conveyor belt unit (twin transparent belts) attached to the ΔT area meter, allowing for a continuous scan by a camera until the entire length of each leaf had passed through.

3.7.2 Plant nutrients

Dried ground (1 mm-mesh) plant material was digested using sulphuric acid-hydrogen peroxide (Allen 1989). The digest was diluted and used for the determination of N, P, K, Ca and Mg (detailed methods in Appendix 5).

An auto-analyser was used for N and P determinations. Nitrogen was determined by the Berthelot reaction (Section 3.5.1), and phosphorus was determined by the Molybdenum Blue Method (Section 3.5.3), with ascorbic acid as a substitute for stannous chloride as the reducing agent. Potassium concentration was determined by flame photometry (Section 3.5.4). Calcium and magnesium were determined by atomic absorption spectrometry (Sections 3.5.4 and 3.5.5), with the use of lanthanum chloride as a releasing agent.

3.7.3 Digestibility of forage maize

Maize digestibility, to assess its value as a feeding forage, was determined by the Neutral Detergent/Cellulase Digestibility method (MAFF 1989). The oil and fat free sample was treated with neutral detergent to extract the cell

contents. Any starch was removed by conversion to soluble sugars through the action of α -amylase. The resultant neutral detergent fibre was thoroughly washed with hot water and digested with buffered cellulase. The indigestible material was filtered and washed and the organic matter of this fraction was determined by ashing. The dry matter and total ash content of the sample were determined separately (MAFF 1986). The percentage of organic matter digested by the neutral detergent and the cellulase was then calculated (Appendix 5).

3.8 Statistical analysis

Analysis of variance followed either by the Student-Newman-Keuls multiple range test or orthogonal contrasts, and repeated measures analysis of variance were carried out, where appropriate, for the statistical analysis of data (USDA 1977; Mead and Curnow 1983; Finney 1988). Statistical packages used included GENSTAT (Genstat 5 Committee 1987), Macintosh SuperANOVA GLM program (Abacus Concepts 1989), and SAS GLM procedure (SAS 1989). The *t*-test of significance was also used for comparison of means from two treatments (Mead and Curnow 1983).

When treatments had heterogeneous variances analysis of variance was carried out on logarithmically transformed data (Finney 1989).

Chapter 4. The 1993 Field Experiment

4.1 Effects of fresh and composted dairy manure on maize (*Zea mays* L.) nutrition, crop production and weed control

4.1.1 Introduction

Inorganic fertilisers used on maize production worldwide are too expensive for small producers, especially for those in developing countries, and this is reflected in low average yields in the short-term (Almeida 1991). However, inorganic fertilisers are unsustainable and are associated with long-term environmental risks such as soil erosion, loss of soil fertility and nitrate pollution of the ground water table (Lockeretz *et al* 1981; Francis *et al* 1986; Magdoff 1991).

Renewable resources available within most farms, such as crop and animal residues, can be recycled into fresh or composted organic fertilisers to improve and sustain soil fertility (Allison 1973; Granstedt 1991; Parr and Hornick 1992). Compost is expected to adequately supply maize nutrient requirements, improving soil fertility with lower risks of nitrate pollution than fresh manures (Chen and Inbar 1993; Maynard 1994).

Forage maize is highly sensitive to weed competition, and fresh animal manures can contain viable weed seeds, increasing the risk of weed infestation (Doran *et al* 1987). The composting process kills weed seeds present in manures and the application of compost has also been reported to help in suppressing weed growth (Dalzell *et al* 1987; Schmalzle 1990).

A production system for maize was studied aiming at reducing dependence on external inputs and at improving the chemical, physical and biological fertility of the soil. Compost was produced with fresh dairy manure and cereal straw. The effects of fresh and composted dairy manure on soil nutritional status, maize nutrition and crop and weed biomass production were studied.

Interactions within the soil-plant system were observed in relation to nutrient supply with and without the presence of weeds. Although less

polluting methods of weed control such as mechanical weeding could have been used for these comparisons, their study did not fall within the objectives of this research, and herbicide was used when the absence of weeds was required.

4.1.1.1 Objectives

The value of fresh dairy manure and dairy manure compost for maize production was considered:

- a) as nutrient suppliers to the soil and to the crop, comparing them with inorganic fertiliser and with each other, and
- b) as weed inhibitors, comparing their relative efficacy with and without herbicide application (atrazine).

4.1.2 Material and methods

A field experiment was conducted in *Orchard Field*, Wye College Estate (Chapter 3), comparing fresh dairy manure, dairy manure compost and inorganic N fertiliser (Nitram) as nutrient suppliers to maize. The area had been previously used for experiments with spring and winter wheat, beans and potato. Prior to treatment application, nutrient analyses of soil from the field (Appendix 2) and of fresh and composted dairy manure (Appendix 3) were carried out. Hereafter, composted dairy manure is referred to as 'compost'.

Compost and manure were incorporated into soil, and compost was also applied as a mulch (Chapter 3), to compare which method would give the best results with respect to crop nutrition and possible weed control.

Two rates of application were used for each treatment (Table 4.1), following the results of a preliminary glasshouse experiment (Chapter 7, Section 7.1) and the recommended nitrogen fertilisation rate for commercial maize in the region (100 kg N.ha^{-1}). Thus, Nitram as topdressing was applied at 50 and 100 kg N.ha^{-1} .

Application rates of compost and manure were equivalent to Nitram in nitrogen availability (Castellanos and Pratt 1981; Brinton 1985; Xie and Mackenzie 1986), corresponding to 30 and $60 \text{ t of compost.ha}^{-1}$, and to 15 and $30 \text{ t of manure.ha}^{-1}$, respectively, both on a fresh weight basis.

Treatments containing both organic (compost and manure) and inorganic fertilisers were also used (compost + Nitram, and manure + Nitram). Organic fertilisers (incorporated) and Nitram (topdressing) were applied at half the rates of their single application, so that each source (organic and inorganic) supplied 50% of the nitrogen applied. Two untreated controls (with no fertiliser) were included for comparison.

Table 4.1 Additives used in 1993 field experiment

Additive	Description	Available N (kg.ha ⁻¹)	Method of Application
1. <i>contA</i>	untreated control	0	N/A
2. <i>contB</i>	untreated control	0	N/A
3. <i>N50</i>	Nitram equiv. to 50 kg N.ha ⁻¹	50	Topdressing
4. <i>N100</i>	Nitram equiv. to 100 kg N.ha ⁻¹	100	Topdressing
5. <i>M50</i>	Manure (15 t.ha ⁻¹) equiv. to <i>N50</i>	50	Incorporated
6. <i>M100</i>	Manure (30 t.ha ⁻¹) equiv. to <i>N100</i>	100	Incorporated
7. <i>MN50</i>	Manure (7.5 t.ha ⁻¹) + Nitram (25 kg N.ha ⁻¹), equiv. to <i>N50</i> in total	50	Incorp. + Topdress.
8. <i>MN100</i>	Manure (15 t.ha ⁻¹) + Nitram (50 kg N.ha ⁻¹), equiv. to <i>N100</i> in total	100	Incorp. + Topdress.
9. <i>C50</i>	Compost (30 t.ha ⁻¹) equiv. to <i>N50</i>	50	Incorporated
10. <i>C100</i>	Compost (60 t.ha ⁻¹) equiv. to <i>N100</i>	100	Incorporated
11. <i>C50m</i>	Compost (30 t.ha ⁻¹) equiv. to <i>N50</i>	50	Mulch
12. <i>C100m</i>	Compost (60 t.ha ⁻¹) equiv. to <i>N100</i>	100	Mulch
13. <i>CN50</i>	Compost (15 t.ha ⁻¹) + Nitram (25 kg N.ha ⁻¹), equiv. to <i>N50</i> in total	50	Incorp. + Topdress.
14. <i>CN100</i>	Compost (30 t.ha ⁻¹) + Nitram (50 kg N.ha ⁻¹), equiv. to <i>N100</i> in total	100	Incorp. + Topdress.

A split-plot design was used to compare the effects of the 14 additives with and without the presence of weeds. Therefore, only one main plot had herbicide (atrazine) application for weed control. This allowed the observation of interactions between weeds and maize nutrition. There were four blocks, giving a total of 112 plots. All additives were fully randomised within each main plot (with and without atrazine) in each of the blocks (Figure 4.1).

General material and methods are described in Chapter 3. A diary of operations is presented in Table 4.2. Destructive Growth Analyses (DGAs) were carried out for maize and weed plants. Due to the large number of subplots, DGAs and soil sampling were limited to only some plots. For soil nutrient analysis, one control (*contA*) plot and all six additives equivalent to 100 kg N.ha⁻¹ (higher application rate) were sampled from all blocks, but in plots with weed control only (with atrazine), giving a total of 28 samples. This allowed investigation of the nutrient supply of treatments to the soil and to the crop in the absence of weed interactions.

For the DGAs, plots with the same seven additives were sampled from all blocks but in both main plots (with and without atrazine application), giving a total of 56 samples. This allowed a correlation of maize growth with soil nutrient levels (in the absence of weeds), and a comparison between maize development both with and without weed competition.

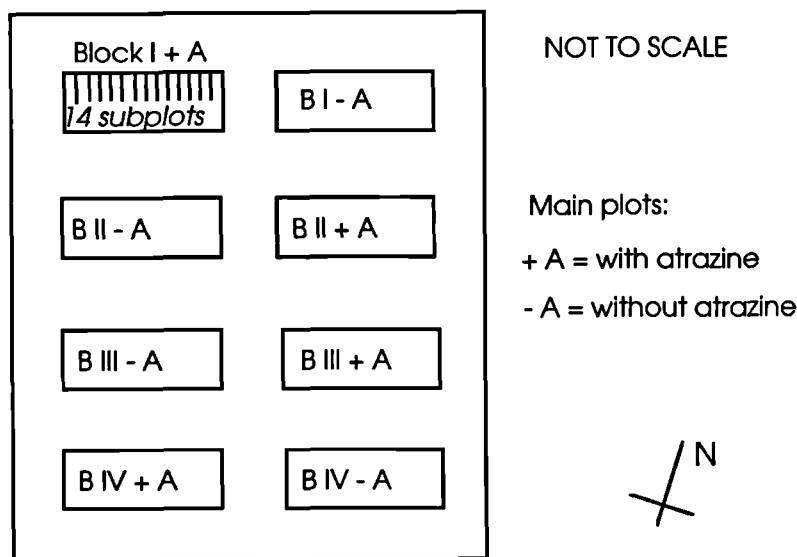


Figure 4.1 Layout of the 1993 field experiment

For soil biological assessments, only one control (*contA*) and Nitram, manure, compost incorporated and compost + Nitram treatments equivalent to 100 kg N.ha⁻¹ were sampled (*N100*, *M100*, *C100* and *CN100*), from blocks I-III in plots with and without weed control (a total of 30 samples). Thus, correlations between soil microbial biomass and activity, crop and weed nutrition were observed.

Table 4.2 Diary of operations in the 1993 field experiment

Date	Operation (inputs added where applicable)
April	Experiment area ploughed
04.05.93	Preliminary soil sampling for nutrient analyses
05.05.93	Compost (C50, C100, CN50, CN100) spread on soil surface
10.05.93	Manure spread on soil surface
11.05.93	Trial area power-harrowed (compost and manure incorporated)
12.05.93	Forage maize (<i>cv. LG2080</i>) drilled Compost (C50m and C100m) applied as a mulch
23.05.93	Crop emergence (maize GS 1.00‡)
27.05.93	Nitram applied as topdressing (maize GS 1.25 - 1 leaf)
28.05.93	Atrazine sprayed (maize GS 1.25)
15.06.93	1st soil sampling for nutrient analysis - (<i>contA</i> , N100, M100, MN100, C100, C100m, CN100), all blocks, plots with atrazine only - (maize early GS 2.25 - 4/5 leaves)
17.06.93	1st soil sampling for biological analysis - (<i>contA</i> , N100, M100, C100, CN100), blocks I-III, plots with and without atrazine - (maize GS 2.25)
24.06.93	1st DGA (maize early GS 2.75 - 6/7 leaves)
12.07.93	2nd soil sampling for biological analysis (maize GS 3.50 - 10 leaves)
15.07.93	Weeds scored
21.07.93	2nd soil sampling for nutrient analysis (maize GS 4.00 - 12 leaves)
29.07.93	2nd DGA, block I (maize GS 4.75 - 15+ leaves, tasseling)
30.07.93	2nd DGA, block II (maize GS 4.75)
02.08.93	2nd DGA, block III (maize early GS 5.00, start of flowering)
04.08.93	2nd DGA, block IV (maize early GS 5.00)
13.08.93	3rd soil sampling for biological analysis (maize GS 5.50, flowering)
19.08.93	3rd soil sampling for nutrient analysis (maize GS 6.00, water ripe)
20.09.93	3rd DGA (maize GS 7.25, half milk ripe - MR)
04.10.93	4th soil sampling for biological analysis (maize GS 7.75, late MR)
05.10.93	4th soil sampling for nutrient analysis (maize GS 7.75)
15.10.93	Harvest (maize GS 8.00 - early dry ripe, physiological maturity)

‡maize Growth Stage (Groot *et al* 1986; Appendix 1)

Soil analyses (methods in Appendix 4) were carried out for determination of total N, $\text{NO}_3\text{-N}$, $\text{NH}_4\text{-N}$, extractable P, K, Ca, Mg, pH, CEC, DM and OM contents. Soil biological analysis using the Fumigation-Incubation methods (Appendix 6) estimated C and N microbial biomass (BC and BN, respectively) and microbial activity ($q\text{CO}_2$).

In each DGA, determinations of maize included plant height, diameter of stem, leaf area index, fresh and dry matter production of whole plant and its parts (leaf, stem + tassel, cob) and nutritional content (N, P, K, Ca, Mg).

In the first and second DGAs, weeds were identified to species and by growth habit, and classified as either grass or broad-leaved (Appendix 7). In all DGAs they were dry weighed and analysed for nutrient content (N, P, K, Ca, Mg). Additionally, between the 1st and the 2nd DGA a weed score was carried out in all subplots. According to growth habit (horizontal or vertical), weed infestation was classified from 0 to 5 in increments of 1, from weed-free to totally infested subplots, respectively (Appendix 8).

Soil temperature of all subplots was measured every fortnight in June and July, in the morning, with the use of a digital thermometer at 5 cm depth. Local and regional meteorological data are presented in Appendix 9.

At harvest, maize fresh and dry matter production per unit area were determined in all subplots, followed by analysis of maize nutrient content (N, P, K, Ca, Mg) and forage digestibility only on the treatments that had been sampled in the DGAs.

Statistical analysis of data was carried out with analysis of variance followed by orthogonal contrasts using GENSTAT (Genstat 5 Committee 1987). Additionally, the fresh and dry matter yield data at harvest were analysed according to their factorial structure within each main plot: the two control treatments were excluded from both main plots, and the remaining twelve treatments in each main plot were analysed according to their 2×6 factorial structure, with two levels of available N (50 and 100 kg $\text{N}\cdot\text{ha}^{-1}$) and six types of fertilisers (or combination of fertilisers).

4.1.3 Results

4.1.3.1 Soil nutrient analyses

Soil pH was not significantly different between treatments, and averaged 8.0. The organic matter content was high, ranging from 4.5 to 5.0% in all sampling dates, with the high rate of compost (C100) having the highest values and the high rate of Nitram (N100) showing the lowest, although a significant difference ($p < 0.01$) between these occurred only at the second soil sampling. Soil $\text{NH}_4\text{-N}$ levels were negligible in all treatments throughout the sampling dates.

An inverse relationship was found between total N (Figure 4.2) and nitrate (Figure 4.3) in soil with Nitram (N100) and with organic (M100, C100 and C100m) treatments. Nitrate levels were significantly higher in Nitram-treated soil than in the control (contA) and organic treatments in the second ($p < 0.05$), third ($p < 0.001$) and fourth ($p < 0.05$) samplings. However, total N levels were significantly higher in organic than in Nitram ($p < 0.001$) and control ($p < 0.01$) plots on the third sampling, and significantly higher in compost- (C100) than in Nitram-treated soil on the fourth sampling ($p < 0.05$).

Table 4.3 Soil extractable P, K and Mg levels (mg.kg^{-1}) with atrazine application in the 1993 field experiment

1993	15 June (1st smpl)			21 July (2nd smpl)			19 Aug (3rd smpl)			5 Oct (4th smpl)		
treats	P	K	Mg	P	K	Mg	P	K	Mg	P	K	Mg
contA	38.6	506	70.3	35.5	310	15.2	29.5	439	13.6	31.2	396	14.2
N100	37.5	229	76.3	28.6	367	15.0	23.9	508	14.0	29.4	571	15.0
M100	43.2	642	81.7	39.0	417	15.8	27.9	518	14.9	34.3	661	16.4
MN100	45.4	375	83.9	36.1	446	16.0	30.0	558	15.2	35.7	552	16.5
C100	46.1	456	89.9	33.7	528	17.7	36.3	569	16.5	44.3	590	20.9
C100m	46.4	315	92.0	43.9	279	14.9	36.9	427	14.4	37.5	489	17.0
CN100	45.9	267	86.6	41.3	510	15.6	36.8	434	15.1	36.4	594	16.9
SED	3.58	136.1	5.69	6.34	101.4	0.97	4.70	80.9	0.69	4.78	104.1	1.70

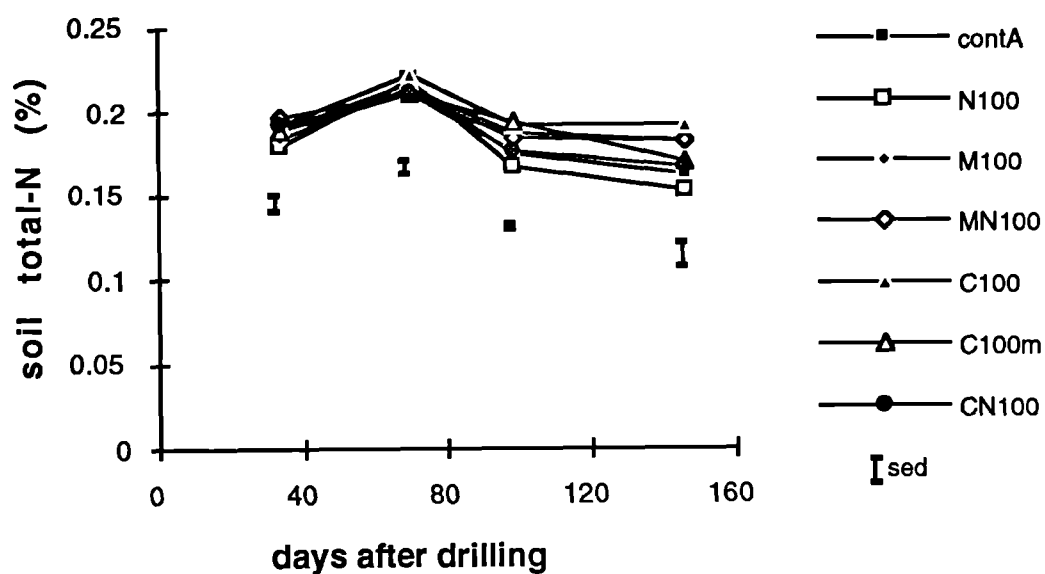


Figure 4.2 Soil total-N % (Kjeldahl) with atrazine application in the 1993 field experiment

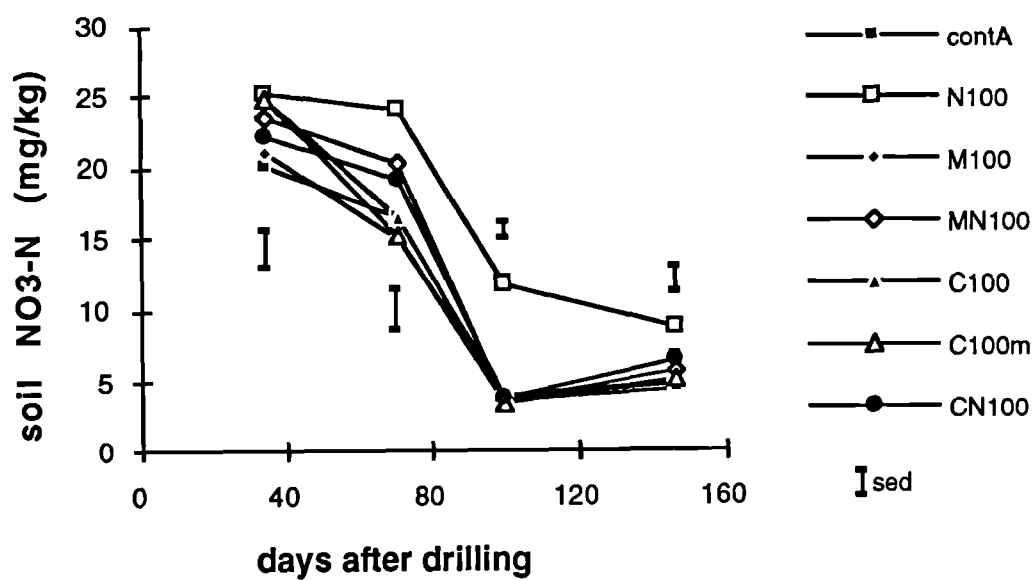


Figure 4.3 Soil nitrate levels (mg.kg⁻¹) with atrazine application in the 1993 field experiment

Soil extractable P, K and Mg results are shown in Table 4.3. No consistent differences were found in K levels between treatments. However, higher soil K and Mg levels ($p < 0.05$) for compost incorporated (C100) than applied as a mulch (C100m) were observed. Compost-treated soil (C100) showed significantly higher levels ($p < 0.05$) of P and Mg than Nitram-treated soil throughout the experiment ($p < 0.01$ in the last sampling).

No significant differences between treatments were found in the soil Ca and CEC levels, which averaged 1300, 1460, 1120, and 1480 mg.kg⁻¹ for Ca, and 18.3, 22.7, 17.2, and 13.3 meq.100 g soil⁻¹ for CEC, respectively, from the first to the last sampling.

4.1.3.2 Soil biological assessments

No consistent differences were found in either microbial biomass carbon (BC, Table 4.4) and nitrogen (BN, Table 4.5) with and without atrazine application. In both main plots, all subplots showed a significant decrease in BC and BN in the third sampling ($p < 0.001$). A trend of recovery of BC and a clear increase in BN ($p < 0.001$) occurred in the fourth sampling.

Table 4.4 Carbon microbial biomass (BC; µg BC.g dry soil⁻¹) with (+ A) and without (- A) atrazine application in the 1993 field experiment

1993	17 Jun (1st sp)		12 Jul (2nd sp)		13 Aug (3rd sp)		4 Oct (4th sp)	
adds	+ A	- A	+ A	- A	+ A	- A	+ A	- A
contA	579	410	610	578	122	204	348	219
N100	618	568	717	703	236	208	560	418
M100	333	434	1264	879	284	318	434	336
C100	743	733	790	770	257	363	518	436
CN100	539	543	688	740	147	217	462	246
		same		same		same		same
	add*A	level A	add*A	level A	add*A	level A	add*A	level A
SED	97.1	105.3	118.4	97.1	51.0	53.9	97.4	94.0

In general, no significant difference was found in BC (Table 4.4) between control (contA), Nitram (N100) and compost + Nitram (CN100) with and without atrazine application. With atrazine application, manure-treated soil (M100) had the lowest BC at the first sampling ($p < 0.05$), and the highest at the second ($p < 0.001$). At the third sampling, compost and manure in general

had significantly higher BC than control and *CN100* ($p<0.05$). Compost was also higher in BC than *N100* without atrazine application ($p<0.05$), but no significant differences were found between compost and manure.

No significant difference was found in BN (Table 4.5) between control, *N100* and *CN100* in both main plots, the exception being in the third sampling without atrazine, where control had the lowest BN ($p<0.001$). In general, manure-treated soil (*M100*) had the highest BN throughout the experiment in both main plots ($p<0.01$), but was only significantly higher than compost (*C100*) in the first sampling with atrazine. Without atrazine application, *C100* was significantly higher than *N100* in both the third ($p<0.01$) and the fourth (0.05) samplings.

Table 4.5 Nitrogen microbial biomass (BN; $\mu\text{g NH}_4\text{-N.g dry soil}^{-1}$) with (+ A) and without (- A) atrazine application in the 1993 field experiment

1993	17 Jun (1st sp)		12 Jul (2nd sp)		13 Aug (3rd sp)		4 Oct (4th sp)	
adds	+ A	- A	+ A	- A	+ A	- A	+ A	- A
<i>contA</i>	84.9	83.5	68.7	71.9	21.6	16.4	75.0	82.4
<i>N100</i>	84.1	90.6	68.2	78.8	27.7	24.0	79.7	72.0
<i>M100</i>	134.9	103.3	108.8	122.2	31.3	36.3	128.7	113.3
<i>C100</i>	102.9	93.2	106.4	96.5	29.2	35.9	100.7	111.0
<i>CN100</i>	98.7	95.4	81.1	79.8	23.8	30.3	83.3	86.0
	<i>same</i>		<i>same</i>		<i>same</i>		<i>same</i>	
	<i>add*A</i>	<i>level A</i>	<i>add*A</i>	<i>level A</i>	<i>add*A</i>	<i>level A</i>	<i>add*A</i>	<i>level A</i>
SED	14.98	9.65	17.82	12.89	3.25	3.14	14.49	14.75

In general, about the microbial activity, expressed as metabolic quotient ($q\text{CO}_2$), there were no consistent significant differences either between the two main plots or between additives (Table 4.6). *M100* had the highest activity in the first sampling ($p<0.01$). At the third sampling, *M100* was not significantly different to *C100*, and both showed the lowest activity ($p<0.05$) both with and without atrazine.

The C/N ratio of microbial biomass averaged 6, 9, 7 and 5, respectively, in the four samplings on plots with atrazine application, and 6, 8, 9 and 4, respectively, without atrazine application. No consistent significant differences were found.

Table 4.6 Microbial activity as metabolic quotient ($q\text{CO}_2$; $\mu\text{g CO}_2\text{-C.h}^{-1}.\mu\text{g BC}^{-1}$) with (+ A) and without (- A) atrazine application in the 1993 field experiment

1993	17 Jun (1st sp)		12 Jul (2nd sp)		13 Aug (3rd sp)		4 Oct (4th sp)	
adds	+ A	- A	+ A	- A	+ A	- A	+ A	- A
<i>contA</i>	0.003	0.002	0.002	0.003	0.009	0.009	0.002	0.009
<i>N100</i>	0.003	0.003	0.002	0.003	0.010	0.009	0.002	0.002
<i>M100</i>	0.006	0.005	0.001	0.002	0.005	0.004	0.005	0.007
<i>C100</i>	0.001	0.001	0.003	0.003	0.004	0.006	0.004	0.006
<i>CN100</i>	0.004	0.002	0.003	0.003	0.013	0.008	0.004	0.009
	<i>same</i>		<i>same</i>		<i>same</i>		<i>same</i>	
	<i>add*A</i>	<i>level A</i>	<i>add*A</i>	<i>level A</i>	<i>add*A</i>	<i>level A</i>	<i>add*A</i>	<i>level A</i>
SED	0.0008	0.0009	0.0011	0.0011	0.0018	0.0019	0.0012	0.0013

4.1.3.3 Maize Destructive Growth Analyses

Results for maize height, stem diameter and fresh biomass production were consistent with leaf area index (Table 4.7) and dry biomass production (Table 4.8), and are shown in Appendix 10. Compost-treated maize (C100) with no weed competition (+ A) had the significantly largest leaf area of all additives ($p < 0.05$) in the last DGA.

Table 4.7 Maize leaf area index (LAI; $\text{m}^2 \text{ leaf area.m}^{-2} \text{ ground area}$) with (+ A) and without (- A) atrazine application in the 1993 field experiment

1993	24 Jun (1st DGA)		29 Jul-4 Aug (2nd DGA)		20 Sep (3rd DGA)	
additives	+ A	- A	+ A	- A	+ A	- A
<i>contA</i>	0.68	0.60	5.42	4.53	4.77	3.60
<i>N100</i>	0.58	0.67	5.83	4.94	5.47	3.91
<i>M100</i>	0.54	0.64	5.79	4.67	4.78	3.48
<i>MN100</i>	0.73	0.62	5.62	4.90	5.68	3.82
<i>C100</i>	0.79	0.61	5.92	4.50	6.78	3.57
<i>C100m</i>	0.58	0.70	6.19	4.14	4.94	3.45
<i>CN100</i>	0.77	0.69	6.20	5.25	5.50	3.89
	<i>same</i>		<i>same</i>		<i>same</i>	
	<i>add*A</i>	<i>level A</i>	<i>add*A</i>	<i>same level A</i>	<i>add*A</i>	<i>level A</i>
SED	0.103	0.097	0.841	0.373	0.845	0.550

The dry biomass production was significantly lower with weed competition (no atrazine applied) at the second ($p<0.01$) and third DGAs ($p<0.05$). No significant difference was found between compost- (C100) and Nitram-treated maize (N100) throughout the experiment, in both main plots. In general, manure-treated maize (M100) had the lowest dry weight ($p<0.05$) in the presence or absence of weeds.

Table 4.8 Maize dry matter production (g.m^{-2}) with (+ A) and without (- A) atrazine application during the 1993 field experiment

1993	24 Jun (1st DGA)		29 Jul-4 Aug (2nd DGA)		20 Sep (3rd DGA)	
additives	+ A	- A	+ A	- A	+ A	- A
<i>contA</i>	31.3	31.2	724	565	2087	1512
<i>N100</i>	28.1	32.4	767	549	2322	1445
<i>M100</i>	26.0	33.6	719	480	1937	1228
<i>MN100</i>	35.6	31.2	755	509	2268	1395
<i>C100</i>	37.6	29.4	744	608	2405	1430
<i>C100m</i>	27.8	35.0	835	448	2128	1292
<i>CN100</i>	39.2	35.5	881	606	2364	1623
	<i>add*A</i>	<i>same level A</i>	<i>add*A</i>	<i>same level A</i>	<i>add*A</i>	<i>same level A</i>
SED	5.48	5.26	95.5	62.2	336.5	224.7

4.1.3.4 Maize harvest

Maize fresh (Figure 4.4) and dry matter yields (Figure 4.5) were significantly lower ($p<0.01$) in the presence of weeds (- A). Plates 4.1 and 4.2 compare maize development in the presence (- A) and in the absence (+ A) of weeds, respectively. Maize dry matter content at harvest averaged 28% with atrazine and 27% without atrazine. No significant differences were found in yields between the two levels of N application for all treatments (50 or 100 kg N.ha^{-1}).

In general, manure-treated maize had the lowest fresh and dry matter yields ($p<0.05$), particularly at the higher level of application (M100) and in the presence of weeds (- A).

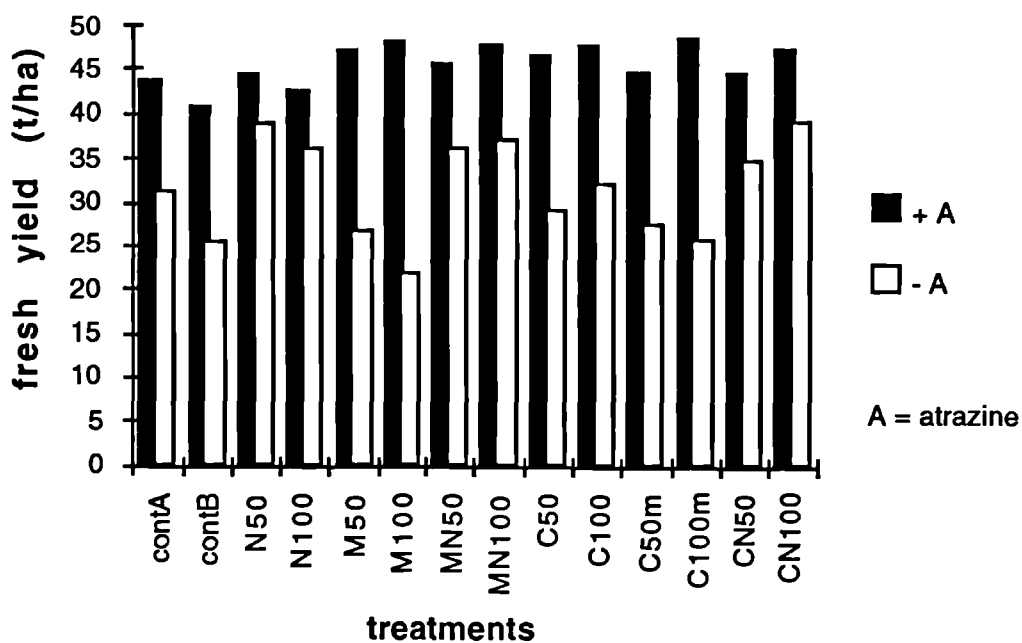


Figure 4.4 Maize fresh biomass yield ($\text{t}\cdot\text{ha}^{-1}$) with (+ A) and without (- A) atrazine application in the 1993 field experiment

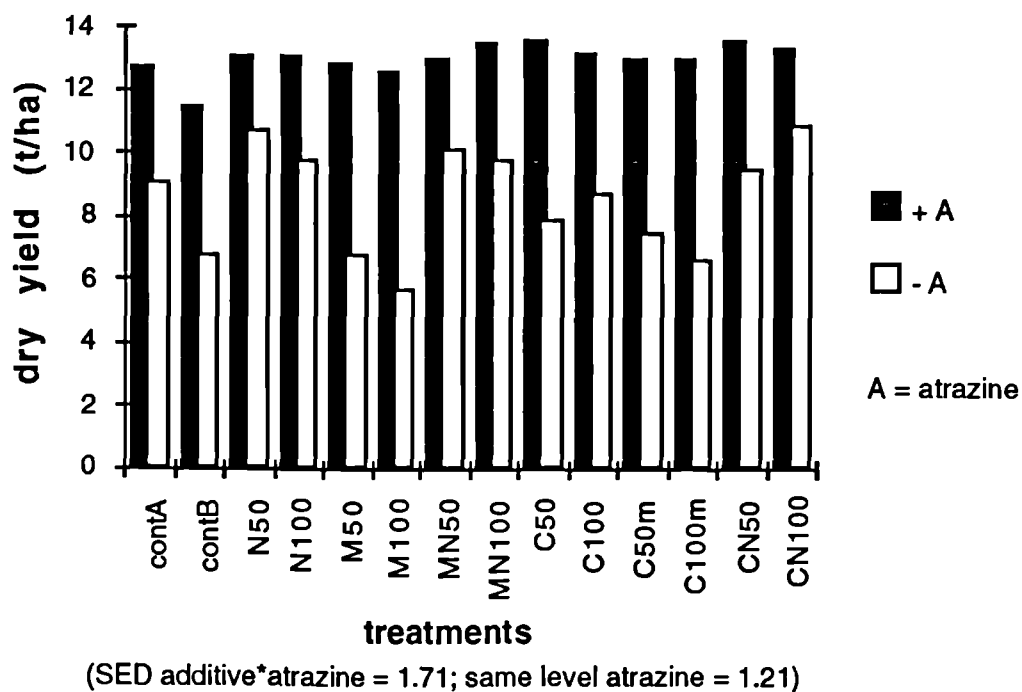


Figure 4.5 Maize dry matter yield ($\text{t}\cdot\text{ha}^{-1}$) with (+ A) and without (- A) atrazine application in the 1993 field experiment



Plate 4.1 Maize development with weed competition (no atrazine applied) in the 1993 field experiment (nutrient deficiency symptoms, plants shorter)



Plate 4.2 Maize development without weed competition (atrazine applied) in the 1993 field experiment (no deficiency symptom, plants taller)

No significant differences were found in yields between compost either when incorporated or applied as a mulch. In general, maize dry matter yields with compost incorporated (C50 and C100) were not significantly different from Nitram (N50 and N100) in both main plots. However, organic additives (particularly compost) had higher fresh biomass yields than control and Nitram ones at the higher level of application (100 kg N.ha⁻¹) without weed competition (+ A).

In the presence of weeds (- A), additives combining organic and mineral N (MN50 and MN100, CN50 and CN100) had significantly higher fresh and dry yields ($p < 0.01$) than the equivalent ones without mineral N (M50, M100, C50, C100, C50m, and C100m), but were not significantly different from the equivalent ones with only mineral N (N50 and N100). A significant interaction occurred between additives in the presence or absence of weeds ($p < 0.01$), as the yields of those with mineral N application differed less between with and without atrazine application than did those without mineral N.

Cob expressed as percentage of dry matter was on average 43% with atrazine application and 35% without atrazine application ($p < 0.05$), but there was no significant difference between additives.

Forage maize digestibility was significantly lower in the presence of weeds ($p < 0.05$), averaging 69.3% with atrazine application and 67.7% without. No significant difference was found between additives.

The nutrient composition in the various plant parts (leaf, stem + tassel, cob) was consistent with the average mineral composition of forage maize DM at maturity, shown in Table 2.1 (Chapter 2), and so is not presented here.

4.1.3.5 Maize nutrient uptake

Nutrient uptake was determined as the amount of nutrient accumulated in the above ground plant parts at harvest, expressed in kg.ha⁻¹. Uptake of N, P, K and Mg by maize were significantly lower ($p < 0.01$) with weed competition (- A). No significant differences were found in nitrogen uptake between additives with atrazine application (Figure 4.6), but Nitram-treated maize had a higher N accumulation than maize from compost incorporated

(C100; $p < 0.05$), manure (M100; $p < 0.01$) and control ($p < 0.05$) plots with weed competition (- A).

Manure-treated maize had the significantly lowest N uptake ($p < 0.05$). No significant differences were found between compost incorporated or applied as a mulch (C100m), although C100m was significantly lower than N100 ($p < 0.05$).

Maize total P, K, Ca and Mg uptake in the two main plots are presented in Table 4.9. No significant differences were found in P uptake between additives with and without atrazine application. Potassium uptake was significantly higher with compost (C100, C100m, CN100) than with Nitram ($p < 0.01$) in the absence of weeds (+ A), but no significant differences were found with weed competition (- A). A significant interaction occurred between additives and main plots, with M100, C100 and C100m showing a larger decrease in K uptake in the presence of weeds ($p < 0.05$).

Table 4.9 Maize total P, K, Ca and Mg uptake ($\text{kg}\cdot\text{ha}^{-1}$) with (+ A) and without (- A) atrazine application in the 1993 field experiment

1993 adds	Phosphorus		Potassium		Calcium		Magnesium	
	+ A	- A	+ A	- A	+ A	- A	+ A	- A
contA	23.0	17.6	92.1	62.5	32.9	21.5	14.1	9.8
N100	23.3	15.7	86.5	68.1	29.9	33.7	14.5	10.7
M100	25.1	11.9	106.7	48.8	28.9	18.5	13.2	6.4
MN100	25.8	18.3	107.5	81.1	32.1	35.1	15.0	11.1
C100	24.2	17.3	116.7	67.5	32.1	24.3	14.0	9.8
C100m	24.8	15.0	117.3	61.9	32.2	25.8	14.3	7.9
CN100	24.6	17.8	106.1	84.2	31.0	28.1	14.6	11.2
	same		same		same		same	
	add*A	level A	add*A	level A	add*A	level A	add*A	level A
SED	3.35	2.37	14.38	10.17	4.94	3.49	1.87	1.32

No significant differences were found in Ca and Mg uptake between treatments with atrazine application. However, a significant interaction occurred in Ca uptake between additives and atrazine application, with N100 and MN100 being significantly higher than M100 ($p < 0.001$) and C100 ($p < 0.05$) in the presence of weeds. Manure-treated maize also had a

significantly lower Mg uptake than *N100* ($p<0.01$) and *C100* ($p<0.05$) without atrazine application.

4.1.3.6 Weed analysis

Atrazine-treated main plots had negligible levels of weed infestation. In the main plots without atrazine application, final weed biomass was significantly higher in Nitram-treated subplots ($p<0.05$) than in manure and compost ones (Figure 4.7).

Prevalent weed species in the field, classified by their growth habit, are shown in Appendix 7. A score of the weed infestation in all subplots, classified by growth habit, is presented in Appendix 8. It was observed that there were patterns of weed species in certain areas of the field, but they were not associated with particular treatments.

Table 4.10 Weed total N, P, K, Ca and Mg uptake ($\text{kg}\cdot\text{ha}^{-1}$) without atrazine application in the 1993 field experiment

treatment	N uptake	P uptake	K uptake	Ca uptake	Mg uptake
<i>contA</i>	21.5	3.8	38.6	25.9	2.6
<i>N100</i>	34.1	5.8	64.4	41.1	4.2
<i>M100</i>	14.0	5.8	30.0	14.5	1.9
<i>MN100</i>	27.3	4.0	51.2	19.3	3.1
<i>C100</i>	17.1	2.7	28.9	10.0	2.1
<i>C100m</i>	17.7	3.0	31.8	17.4	2.0
<i>CN100</i>	18.8	3.1	31.6	14.9	2.3

Weed nutrient uptake was negligible in atrazine-treated main plots. It is presented in Table 4.10 for the main plot without atrazine application only. In general, weeds in Nitram-treated subplots had higher N, P, K, Ca and Mg uptake than in the other treatments, although no statistical analysis was possible as data were from all blocks bulked together.

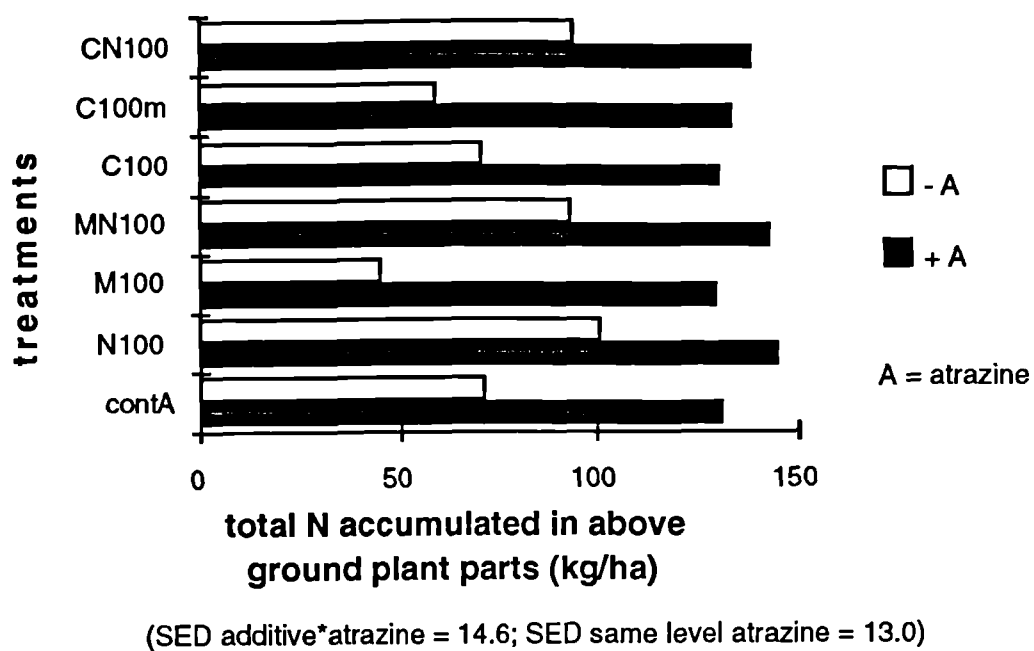


Figure 4.6 Maize total nitrogen uptake ($\text{kg} \cdot \text{ha}^{-1}$) with and without atrazine application in the 1993 field experiment

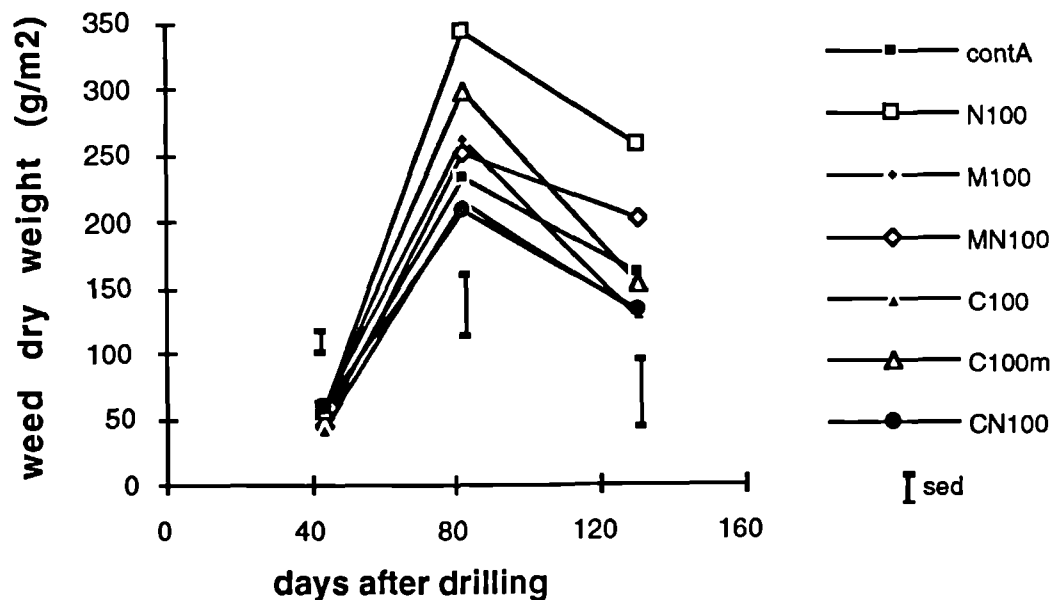


Figure 4.7 Weed dry biomass production ($\text{g} \cdot \text{m}^{-2}$) without atrazine application during the 1993 field experiment

4.1.3.7 Soil temperature

No significant differences were found in soil temperature between treatments in both main plots (results not presented), but temperature was significantly higher in the atrazine-treated main plot when maize was at GS 3.00-4.00 (Groot *et al* 1986; Appendix 1).

4.1.4 Discussion

The high organic matter content originally in the soil was a source of nutrients and probably contributed to masking possible treatment effects, explaining the few significant differences between additives and the control in relation to the parameters measured in this experiment. Nevertheless, the high levels of nutrients present in compost still resulted in higher levels of nutrients (total-N, P, K, Mg) in compost-treated soil. The trend of higher K and Mg levels in soil under compost incorporated than applied as a mulch suggests a better mineralisation of these nutrients when incorporating than mulching the compost.

The lack of significant differences found in Ca levels were probably a result of the high Ca content of the soil (a calcareous silt loam, initial analysis in Appendix 2). The pH level was considered adequate for microorganisms and for maize, which yields best in pH ranging from 6 to 8 (Kiehl 1985; Fageria *et al* 1991). The low $\text{NH}_4\text{-N}$ levels found are consistent with results from Cassman and Munns (1980) and Rochester *et al* (1992), indicating negligible ammonium levels in aerated, alkaline soils during plant growth. Nitrate dominates the mineral N component of these soils as nitrification processes are rapid in high pH conditions and ammonia loss by volatilisation may also occur (Hébert *et al* 1991; Rochester *et al* 1992).

Results of higher total N and lower nitrate levels in soils with organic treatments, particularly with compost application, suggest that compost-N mineralises relatively slowly, reducing the risk of N losses (Zaccheo *et al* 1993; Robertson and Morgan 1995). Thus, compost has a lower potential for nitrate leaching and ground water pollution than mineral fertilisers (Vogtmann 1984; Maynard 1993).

The excess of soil nitrate in Nitram treatments at the beginning of maize development was potentially leached, as maize's uptake is minimal during

initial stages of plant growth, increasing steadily to reach a maximum between flowering and early grain formation (Pain 1978; Fageria *et al* 1991). The accentuated decrease of soil nitrate levels in all treatments at the third sampling and the overall decrease in microbial biomass confirms that flowering (maize GS 5.50, Groot *et al* 1986) is the period of higher N uptake by maize.

The higher nitrate levels in Nitram treated plots was not correlated with higher maize fresh and dry matter yields, but with an increase in weed biomass and N uptake, suggesting that weeds benefited most from the extra $\text{NO}_3\text{-N}$ available. No difference in maize yields and the few differences found in BC and BN levels between treatments indicate that nutrient levels were adequate for maize and microorganism development under all treatments, probably due to the high organic matter content initially in the soil.

The Fumigation-Incubation method used in this experiment for microbiological determinations is not recommended when organic materials have been recently added to soil (Jenkinson 1988, Kaiser *et al* 1992), as the potential for N immobilisation by the recolonising microbial population during the incubation may lead to an unreliable estimate of BN (Carter 1991). Therefore, results obtained in this experiment should be treated with caution.

Microorganisms are apparently more competitive for nutrients than are plants, and are not affected by atrazine application, as the absence of differences in BC and BN results between the two main plots indicates. As observed by Ghoshal and Singh (1995), microbial BN was at its highest with addition of substrate (either fertilisers at the beginning, or plant material such as senescent leaves and roots at the end of the crop cycle) and when plant nutrient uptake was lower (at the beginning and the end of the maize development, Pain 1978). During maize flowering, an accelerated uptake of N by the crop caused intensive competition for nutrients and limited the nutrient availability for microorganisms.

Carbon is the limiting factor in microbial biomass production (Fauci and Dick 1994a; Ghoshal and Singh 1995). Nitram inputs did not supply any C to microorganisms, and so did not result in higher BC and BN production despite the high levels of mineral N availability. Compost-treated soil had

the highest BC at the peak of competition with maize and weeds (maize flowering without atrazine application), proving a better nutrient supplier for microorganisms. The higher BN with manure and compost treatments indicate that microorganisms have higher biomass production with organic inputs (Anderson and Domsch 1989; Wardle 1992). This is due both to the presence of C and to a more efficient use of organic N than plants, which had higher N uptake in treatments with mineral N.

Soil microbial biomass is an important reservoir of nutrient for crop growth, being essential for soil fertility (Ghoshal and Singh 1995; McCarty *et al* 1995). Microorganism biomass is the most available source of nutrients to plants after mineralisation, thus a higher biomass content reflects in higher availability of nutrients to plants (Jenkinson and Ladd 1981). The higher biomass in compost and manure treatments suggests that the N was being mineralised and taken up by the microorganism biomass, thus being potentially available to plants later.

The high C/N ratio of the manure applied (around 30, Appendix 3) resulted in high N immobilisation in manure-treated soil. Higher microbial activity can be associated with conditions of disturbance (Wardle and Ghani 1995). The intense microbial activity shortly after manure application indicates that at that stage microorganisms were adapting to the new substrate added (lag stage without C biomass production), and were spending more energy to take up the nutrients. Results of high BC and BN thereafter suggest that microorganisms started making use of the high levels of C of the substrate and balancing their C/N ratio through immobilisation of soil N.

On the other hand, compost had a stable C/N ratio of around 10 (Appendix 3), which is similar to those found in soils. Moreover, humic acids from dairy manure compost are similar to soil humic acids (Deiana *et al* 1990). Hence, no period of adaptation was necessary for microorganisms in compost-treated soil. These microorganisms had an adequate supply of nutrients throughout crop development, as indicated by the low metabolic quotient in compost-treated soils (Wardle and Ghani 1995). The absence of significant differences in microbial biomass and activity between manure and compost treatments at the last samplings indicate that by that stage manure had also stabilised its C/N ratio.

Soil is a very complex system with several factors interacting at any given moment. Microbial activity is dependent on soil water content, soil temperature, substrate added, availability of nutrients, BC and ecological succession, among others (Ross *et al* 1995). The metabolic quotient increased for all treatments coinciding with maize flowering, indicating the higher stress caused by nutrient competition, although part of the increase can also be attributed to higher soil temperature and moisture at that period (Doran *et al* 1987; Wardle and Ghani 1995).

Changes in microbial biomass C/N ratio during the experiment can be explained by ecological succession. The C/N ratio ranges from 3-6 for bacteria biomass and 6-12 in fungi biomass (Wardle 1992). The higher average C/N ratio at first indicates the predominance of fungi, which decompose more complex molecules such as lignin and cellulose. The lower C/N at the end indicates that bacteria are then predominant, attacking the molecules that had been broken down by the fungal population. Moreover, higher levels of N available result in lower C/N ratio in the beginning and at the end of the crop development, and the higher competition for N at the intermediary stages is reflected in higher C/N ratio of the microbial biomass.

The lowest fresh and dry matter yields in manure-treated maize, even in relation to the control, particularly without atrazine application can be explained by the higher competition for nutrients from both the weeds and the microorganisms, which had higher microbial biomass with manure application during the stem elongation stage of maize development (Groot *et al* 1986). There was a synergistic effect in reducing maize yields due to competition from both weeds and microorganisms for nutrients.

Nitrogen and potassium are required in equivalent quantities by the plant (Marschner 1986). Fresh and composted dairy manure have high levels of K, and maize has a high demand for it, thus resulting in higher K levels in manure- and compost-treated maize. Low levels of Ca and Mg in compost-treated maize were a consequence of the high rates of K, as the sum of K, Ca and Mg individual percentages is generally constant in plants at all growth stages, with variation only in the content of individual nutrients (Pain 1978).

The higher leaf area index and fresh biomass yields on compost-treated maize at the end suggests an effect of compost in delaying maize maturity.

The higher leaf area index could be due to delayed leaf senescence, suggesting that leaves were still active, photosynthesising nutrients. That could indicate that the crop had probably not yet reached its full production potential by then. Higher fresh biomass yield could be due to higher K accumulation in compost-treated maize, as K plays a major role in water and nutrient absorption by the plant (Marschner 1986). Plants well supplied with K show increased uptake of water and reduced water loss (Mengel and Kirkby 1987). Higher fresh yield and leaf area index in compost-treated maize could also be due to the stimulatory effect of humic substances on plant nutrition and growth due to both a direct action of low molecular weight humic molecules of compost on plasma membrane H⁺-ATPase and modification of cell membrane permeability, increasing passive permeability to protons (Varanini *et al* 1993). Hence, maize continued to absorb nutrients over a longer period of time with compost application, delaying its senescence and maturity. Additionally, higher fresh biomass yield might be due to higher soil water availability in compost-treated soils (Kiehl 1985; Dalzell *et al* 1987), increasing water absorption by plants.

However, higher fresh biomass yield was not correlated with higher dry matter yield, as maize had lower dry matter content with compost application than with Nitram. Therefore, no significant differences were found between these treatments in maize dry biomass production.

The need for weed control in maize was clearly indicated by much lower yields in the main plots without atrazine application. The slow growth in the early stages of development and the big inter-row spacing contribute to maize being highly affected by weed competition (Bunting 1978; Doran *et al* 1987). Compost mulch showed no significant effect in weed control, contrary to suggestions found in the literature (Titov and Babakov 1988; Schmalzle 1990; Lee *et al* 1992; Ligneau and Watt 1995).

In the conditions of this experiment, no significant differences in yields were found between compost incorporated or applied as a mulch. However, under drought conditions a mulch could result in higher biomass yields due to its effect in increasing soil water retention (Lal 1974; Wardle *et al* 1993).

The cob as percentage of dry matter is an important parameter in assessing forage quality, as it is the most digestible part of the plant (Wilkinson 1978).

The presence of weeds clearly reduced forage quality, by reducing maize's cob percentage through competition, and by reducing forage digestibility probably due to the presence of weeds from the rows, that were harvested with the maize.

The lower soil temperatures in the main plot without atrazine were probably due to the effect of weeds in shading the soil.

Maize is a tropical crop, and so responds better to treatments in warmer conditions than the UK. Differences in yield might be more evident under poorer soil nutrient conditions, and also with warmer weather conditions (Appendix 9). The short period of time for observation of the effects of compost application may also have contributed to the few consistent differences in maize and microbial biomass found. Moreover, several factors interact in the soil-plant system, making it difficult to demonstrate any difference due to treatment effects in field conditions.

4.1.5 Conclusions

Maize is highly sensitive to weed competition. Maize fresh and dry matter yields and forage feeding quality are lower in the presence of weeds.

Organic inputs, including compost applied as a mulch, are apparently not effective as weed inhibitors. However, higher weed growth appears to result from higher nitrate levels in Nitram-treated soils.

The use of fresh manures with high C/N causes N immobilisation by the soil microbial biomass resulting in lower maize yields. Therefore, composting is recommended prior to application.

No differences in biomass yields result from application of compost as a mulch or when incorporated if conditions of water availability are adequate. However, incorporation appears to result in better nutrient availability.

Compost has a lower potential for nitrate leaching and pollution than mineral fertilisers.

Lower nitrate and total N levels in soil and lower microbial biomass demonstrate higher N uptake by maize during its flowering.

Microorganisms appear to be more competitive than maize in taking up nutrients in the presence of weeds. However, during periods of higher N uptake by maize, microbial biomass decreases and activity increases due to the stress conditions (nutrient competition).

Microorganisms are apparently not affected by the atrazine itself, although any possible response might be more evident over a longer period of time.

Organic inputs result in higher microbial biomass production, a potential source of nutrient availability to the crop.

The possible effect of compost in delaying maize maturity should be investigated with the use of a shorter cycle maize variety.

Experiments conducted in a warmer climate and/or with the use of soil with a low nutrient and low organic matter contents might demonstrate larger treatment effects in soil and plant nutrient contents and in maize yields.

Long term observations are needed to allow a better understanding of possible residual effects of organic inputs in soil chemical and biological fertility (building up of microbial biomass and nutrients) and maize production.

Chapter 5. The 1994 Field Experiments

5.1 Field A - Effects of dairy manure compost on soil fertility, maize (*Zea mays* L.) production and weed growth

5.1.1 Introduction

Results from the 1993 field experiment (Chapter 4) indicated that the use of dairy manure compost could supply the nutrients required for maize production, by improving soil chemical and biological fertility (Suzuki *et al* 1990; Wardle 1992; Giusquiani *et al* 1995).

Thus, by recycling farm organic residues, maize could be produced with lower dependence on external fertilisers (Magdoff 1991; van der Werf 1993). Moreover, the results of the 1993 field experiment suggest that compost application would improve soil fertility, with less risk of nitrate pollution of ground water table than fresh manures and inorganic fertilisers (Vogtmann 1984). Compost also appeared to result in less weed growth than the latter, as suggested by Dalzell *et al* (1987).

However, although effects of compost application have been studied in soil nutrient status, weed growth and crop production, there is an incomplete understanding on how these factors interact together with the biological effects of adding compost to soil. Microorganisms play a major role in the mineralisation and thus plant availability of macro and micro nutrients, having direct and indirect effects on soil nutrient supply (Jenkinson and Ladd 1981; Visser and Parkinson 1992).

A field experiment was conducted to further examine the effects of dairy manure compost (produced with fresh dairy manure and cereal straw) on soil chemical and biological fertility, maize nutrition and crop and weed biomass production. Special emphasis was given in attempting to understand more about the biological effects of compost application to soil.

As in the 1993 field experiment, interactions within the soil-plant system were observed in relation to nutrient supply with and without the presence of weeds.

5.1.1.1 Objectives

This experiment aimed at a more detailed understanding of the effects of applying dairy manure compost to maize crops. In particular the soil as a biological and chemical medium of nutrients for maize growth was studied. There was a focus upon the dynamics of soil microbial biomass and activity, and on mineralisation of compost nutrients. Effects of compost on crop and weed biomass production were compared with those of inorganic fertiliser application.

5.1.2 Material and methods

A field experiment (named Field A) was carried out in *Orchard Field*, Wye College Estate (Chapter 3), in spring 1994. The area had been under commercial oat cultivation in the previous year (1993). The 1994 Field A experiment compared inorganic N fertiliser (Nitram) and dairy manure compost at two rates of application. One was the recommended nitrogen fertilisation rate for commercial maize in the region (100 kg N.ha⁻¹). A doubled rate (200 kg N.ha⁻¹), was used for comparison. The latter is the recommended rate for maize in Italy, where an experiment with similar methodology would be carried out in 1995 (Chapter 6), for comparison of results in different climatic conditions.

General material and methods are described in Chapter 3. Soil and compost samples were taken for nutrient (Appendices 2 and 3, respectively) and biological analyses (soil only), prior to any treatment application.

In the 1993 field experiment (Chapter 4), no significant differences in maize production were found between compost either incorporated or applied as a mulch, although incorporation appeared to promote a better mineralisation of compost nutrients in the soil. Hence, in this 1994 experiment, compost was only incorporated in the soil. Compost amounts were equivalent to Nitram ones in terms of N availability (Brinton 1985). Untreated controls (no fertiliser) were included. Herbicide (clopyralid) was used for weed control in some treatments (+ herb), but others were unsprayed (- herb), for comparison (Table 5.1). As the herbicide was not effective in controlling weeds, a brush weeder (Plate 5.1) and a hoe were used in these plots, and the rows were hand weeded.

Table 5.1 Treatments used in 1994 Field A experiment

Treatment	Description	Available N (kg.ha ⁻¹)	Weed control
1. <i>cont</i> +	untreated control with (+) herbicide	0	yes
2. <i>cont</i> -	untreated control without (-) herbicide	0	no
3. <i>N100</i> +	Nitram equiv. to 100 kg N.ha ⁻¹ + herb	100	yes
4. <i>N100</i> -	Nitram equiv. to 100 kg N.ha ⁻¹ - herb	100	no
5. <i>N200</i> +	Nitram equiv. to 200 kg N.ha ⁻¹ + herb	200	yes
6. <i>C100</i> +	Compost (50 t.ha ⁻¹) equiv. to <i>N100</i> + herb	100	yes
7. <i>C100</i> -	Compost (50 t.ha ⁻¹) equiv. to <i>N100</i> - herb	100	no
8. <i>C200</i> +	Compost (100 t.ha ⁻¹) equiv. to <i>N200</i> + herb	200	yes

A randomised complete block design with four blocks was used, giving a total of 32 plots (Figure 5.1). A diary of operations is presented in Table 5.2.

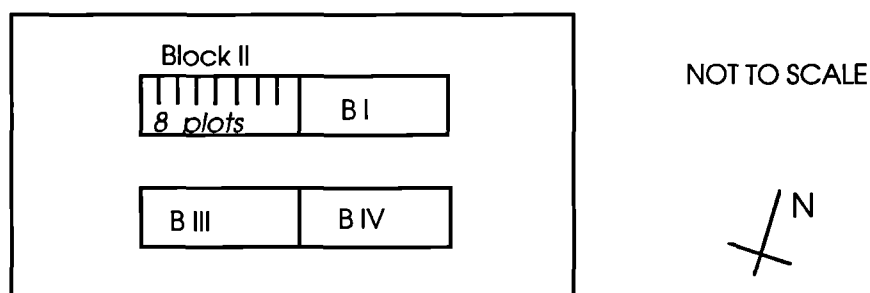


Figure 5.1 Layout of the 1994 Field A experiment

Soil nutrient analyses (total N, NO₃⁻, NH₄⁺, extractable P, K, Ca, Mg, pH, dry matter and organic matter) were done at Wye College (methods in Appendix 4). Determinations of soil Ca and pH were only done at the first soil sampling, as they showed no significant variation with neither time nor treatment in the 1993 field experiment. Soil biological assessments (C and N microbial biomass - BC and BN, and microbial activity - *q*CO₂) using the Fumigation-Extraction method (Appendix 6) were carried out by the Department of Agrobiological and Agrochemistry at *Università degli Studi della Tuscia*, in Viterbo, Italy.

Table 5.2 Diary of operations in the 1994 Field A experiment

Date	Operation (inputs added where applicable)
April	Experiment area ploughed
25.04.94	Preliminary soil sampling for nutrient and biological analyses
04.05.94	Compost spread on soil surface
05.05.94	Trial area power-harrowed (compost incorporated)
06.05.94	Forage maize (<i>cv. LG2080</i>) drilled
13.05.94	Nitram applied as topdressing
19.05.94	Crop emergence (maize GS 1.00†)
13.06.94	Clopyralid sprayed (maize GS 1.75 - 2/3 leaves)
27.06.94	1st soil sampling for nutrient and biological analyses (maize GS 2.25 - 4/5 leaves)
28.06.94	Brush weeding in the + herb plots, hand weeding in rows (maize GS 2.25)
08.07.94	Mechanical hoe used (+ herb plots; maize GS 2.75 - 6/7 leaves)
12.07.94	Hand weeding in rows (+ herb plots; maize GS 3.00 - 7/8 leaves)
28.07.94	1st DGA (maize GS 4.00 - 11/12 leaves)
22.08.94	2nd soil sampling for nutrient and biological analyses (maize GS 5.75 - end of flowering)
13.09.94	2nd DGA (maize GS 7.25 - half milk ripe)
26.09.94	3rd soil sampling for nutrient and biological analyses (maize GS 8.00 - early dry ripe, physiological maturity)
05.10.94	Harvest (maize GS 8.25 - dry ripe)

†maize Growth Stage (Groot *et al* 1986; Appendix 1)

Maize samples (Destructive Growth Analysis - DGAs) were taken at two stages for determination of fresh and dry biomass, leaf area index and nutrient content (N, P, K, Ca, Mg). Plots without weed control (- herb), were sampled at both their extremes, as described in Chapter 3. However, in plots with weed control (+ herb), maize suffered from weed competition at first, as the herbicide failed to control weeds, and from mechanical weeding after, as some maize plants were destroyed by the equipment, thus presenting an uneven pattern of development within treatments and within rows. Because of the high variability of maize development in these plots (+ herb), samples were taken from the areas least affected by weeds and weeding, that had been previously marked with canes.

Weeds were also sampled in the DGAs, for dry biomass and nutrient content. The weed species present were the same as in the 1993 field trial, and are listed in Appendix 7.

Final maize fresh and dry matter production per unit area were determined at harvest. Subsequently, maize nutrient content (N, P, K, Ca, Mg) and forage digestibility were also determined.

Analysis of variance followed by orthogonal contrasts was carried out using the Macintosh SuperAnova GLM program (Abacus Concepts 1989) for the statistical analysis of data. Some of the data had to be logarithmically transformed for the analysis of variance, due to heterogeneity of variance (Finney 1989).

5.1.3 Results

5.1.3.1 Soil nutrient analyses

No significant differences were found between treatments in soil pH and Ca levels, their average being 8.0 and 1543 mg.kg⁻¹, respectively. Soil organic matter content was also not significantly different between treatments throughout the experiment, averaging 4.5% in control and Nitram treatments and 4.9% in compost treatments.

Soil dry matter content was significantly lower in compost- than in Nitram-treated soil (data not presented; $p < 0.05$; averaging 85.7% and 86.9%, respectively) in the second sampling only.

At the first sampling, soil total-N content was significantly higher ($p < 0.01$; Figure 5.2) at the higher level of Nitram application (N200+) than at the lower (N100+ and N100-), but no significant differences were found between Nitram and compost treatments. However, at the final sampling, plots with the higher level of compost application (C200+) had the highest total-N levels ($p < 0.05$). In general, no significant difference was found in total-N levels of soils with (+ herb) or without (- herb) herbicide application.

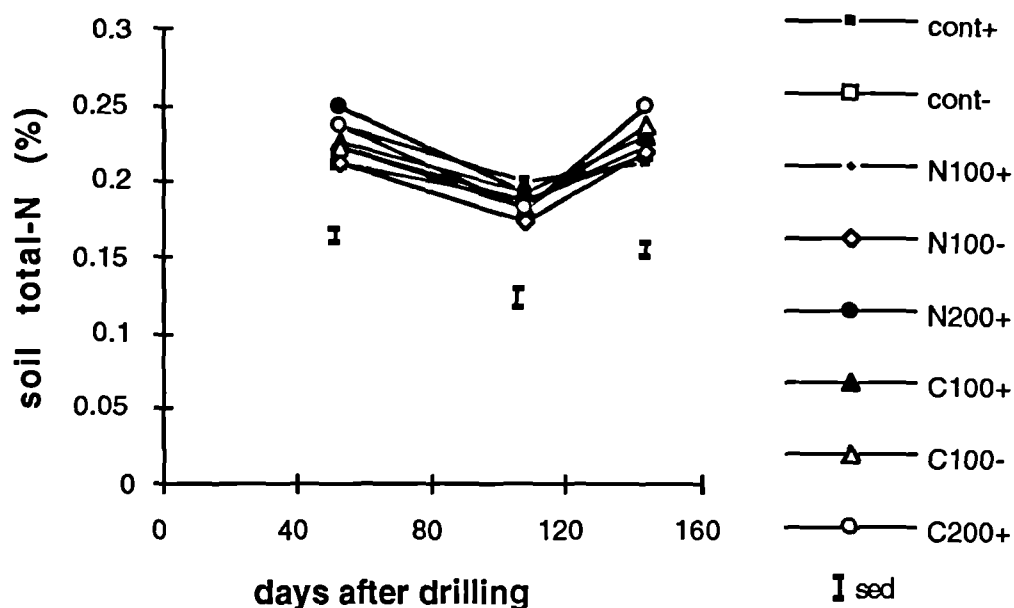


Figure 5.2 Soil total-N % (Kjeldahl) in the 1994 Field A experiment

Table 5.3 Soil extractable P, K and Mg levels (mg.kg⁻¹) in the 1994 Field A experiment

1994 treats	27 June (1st sampling)				22 Aug (2nd sampling)				26 Sep (3rd sampling)			
	P	K [‡]	logK	Mg	P	K [‡]	logK	Mg	P	K [‡]	logK	Mg
<i>cont+</i>	58.2	185	2.3	48.4	39.7	149	2.2	48.2	55.5	201	2.3	45.3
<i>cont-</i>	50.9	125	2.1	42.9	42.1	120	2.1	45.2	65.1	216	2.3	45.2
<i>N100+</i>	66.0	192	2.3	50.1	42.7	149	2.1	47.6	59.3	275	2.4	54.5
<i>N100-</i>	64.5	162	2.2	46.4	37.5	105	2.2	46.6	54.2	246	2.4	50.5
<i>N200+</i>	62.1	192	2.3	51.9	39.3	127	2.1	47.0	66.8	283	2.4	57.3
<i>C100+</i>	62.3	237	2.3	55.8	52.1	338	2.5	61.4	67.3	417	2.6	64.9
<i>C100-</i>	57.6	252	2.4	54.2	49.9	302	2.4	57.0	67.1	469	2.7	60.7
<i>C200+</i>	60.6	401	2.6	54.3	54.7	441	2.6	57.4	89.4	706	2.8	76.0
SED	7.02		0.16	7.32	5.38		0.12	6.39	6.12		0.09	7.58

[‡] statistical analysis of K data carried out on logarithmically transformed data (*logK*)

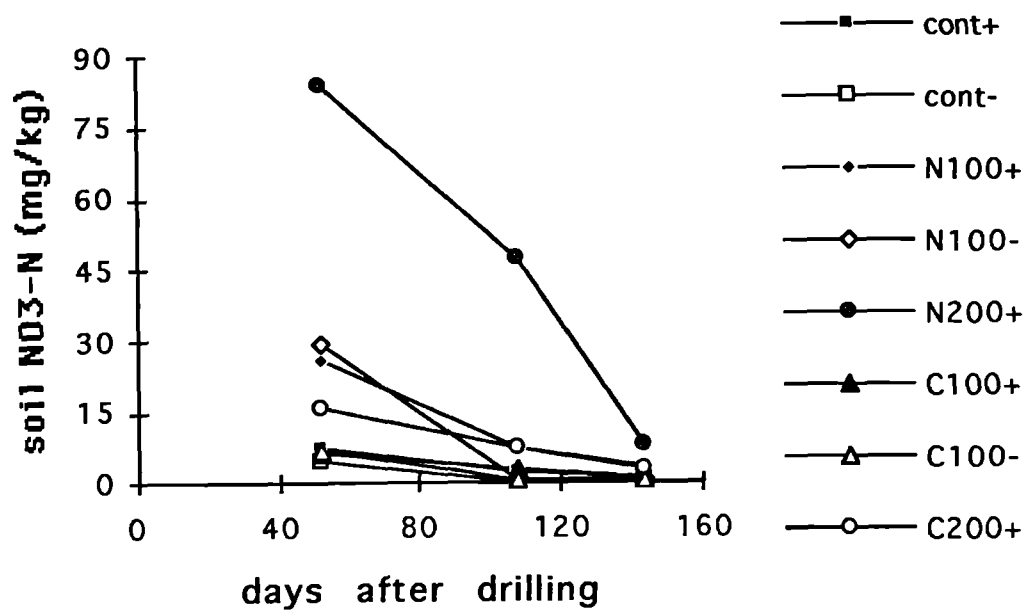


Figure 5.3 Soil nitrate levels (mg.kg⁻¹) in the 1994 Field A experiment (raw data)

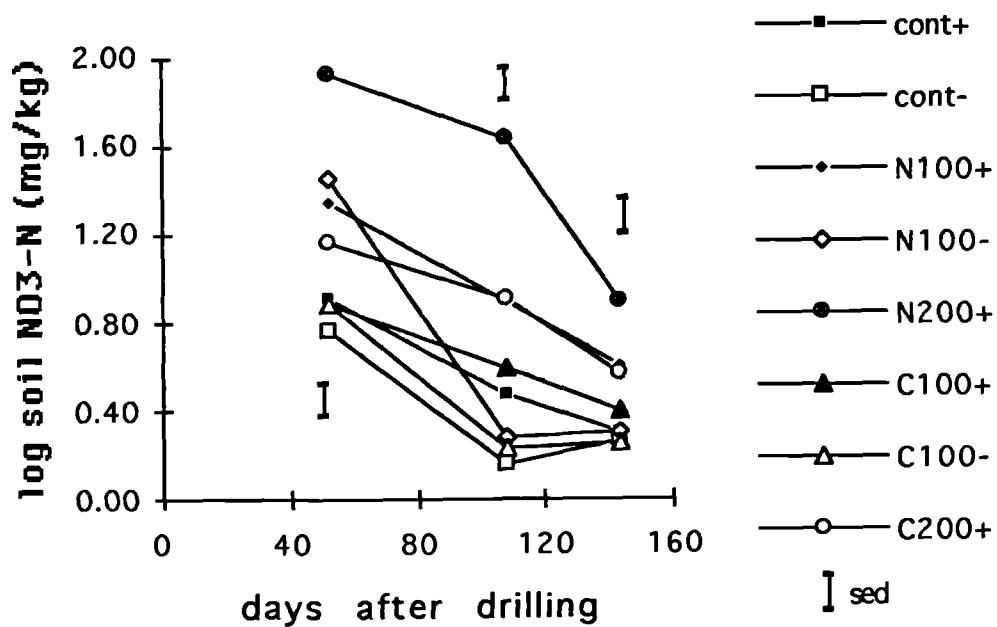


Figure 5.4 Soil nitrate levels (mg.kg⁻¹) in the 1994 Field A experiment (logarithmically transformed data)

Only traces of soil $\text{NH}_4\text{-N}$ were found in all treatments during the experiment. Soil nitrate levels, which were around 8.5 mg.kg^{-1} prior to treatment application, showed a sharp increase in Nitram-treated plots (Figure 5.3, raw data): N200+ had the highest $\text{NO}_3\text{-N}$ levels of all treatments ($p < 0.001$) in the first and second samplings (Figure 5.4, logarithmically transformed data), and N100+ was significantly higher ($p < 0.01$) than C100+ only at the first sampling. However, no significant differences were found between the two rates of application of compost (C100+ and C200+). Nitrate levels were significantly lower in plots with the presence of weeds (- herb) in the second sampling ($p < 0.001$).

In general, compost-treated soil had significantly higher soil extractable P, K, and Mg levels (Table 5.3; $p < 0.01$, $p < 0.001$ and $p < 0.05$, respectively) than Nitram and control plots at the second and third soil samplings. At the last sampling, these levels largely increased in C200+ plots, which also had significantly higher P ($p < 0.01$) and K ($p < 0.05$) levels than other compost-treated plots. No significant differences were found in the soil levels of P, K and Mg between plots with (+ herb) or without (- herb) weed control.

5.1.3.2 Soil biological assessments

Results of soil biological determinations prior to treatment application in the experimental area were on average: carbon biomass (BC) = $305.2 \text{ } \mu\text{g BC.gds}^{-1}$; nitrogen biomass (BN) = $80.1 \text{ } \mu\text{g NH}_4\text{-N.gds}^{-1}$; microbial activity (expressed as metabolic quotient - $q\text{CO}_2$) = $0.006 \text{ } \mu\text{g CO}_2\text{-C.h}^{-1}.\mu\text{g BC}^{-1}$. The microbial biomass C/N ratio was approximately 4.

No significant differences were found in either C and N microbial biomass (Figures 5.5 and 5.6, respectively) or microbial activity (Figure 5.7) between plots with (+ herb) and without (- herb) weed control.

In general, a trend of decrease in BC and BN in the second sampling occurred in all plots, followed by a slight increase in the third sampling in compost and Nitram plots. No significant differences were found in BC and BN between Nitram and compost plots, both having in general significantly higher microbial biomass than control plots ($p < 0.05$). However, BC tended to be higher in compost- than in Nitram-treated soil, at equivalent rates of N application.

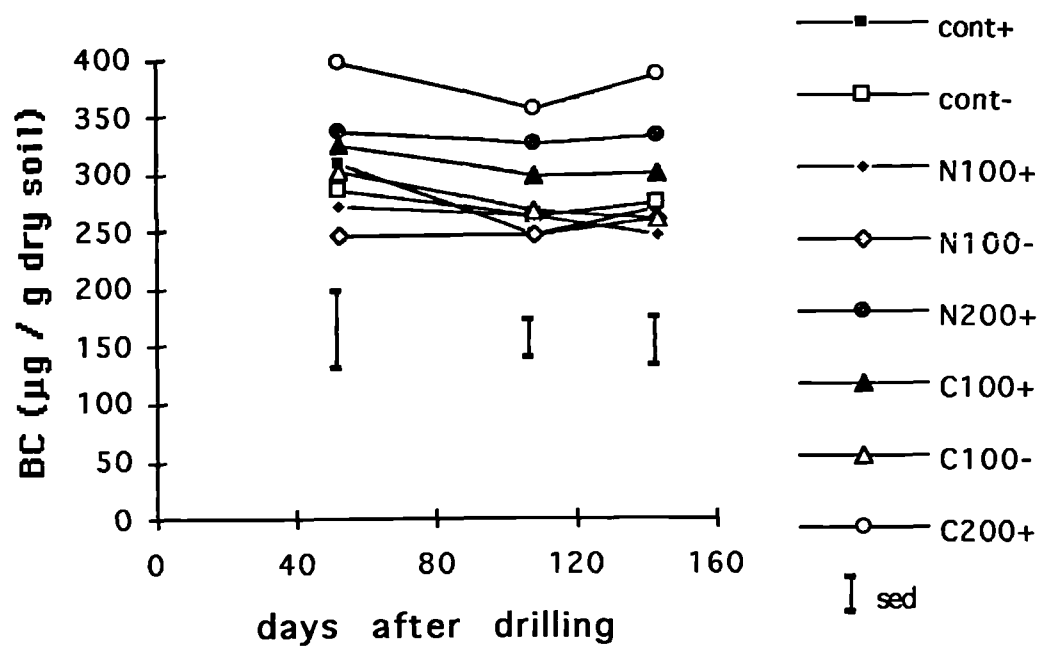


Figure 5.5 Carbon microbial biomass (BC; $\mu\text{g BC.gds}^{-1}$) in the 1994 Field A experiment (gds = g dry soil)

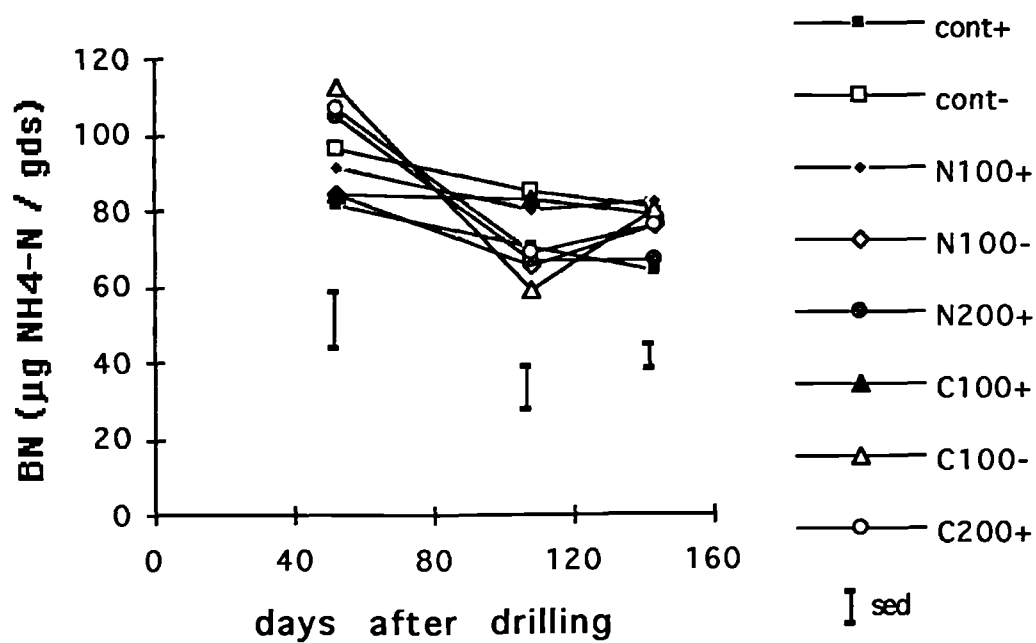


Figure 5.6 Nitrogen microbial biomass (BN; $\mu\text{g NH}_4\text{-N.gds}^{-1}$) in the 1994 Field A experiment (gds = g dry soil)

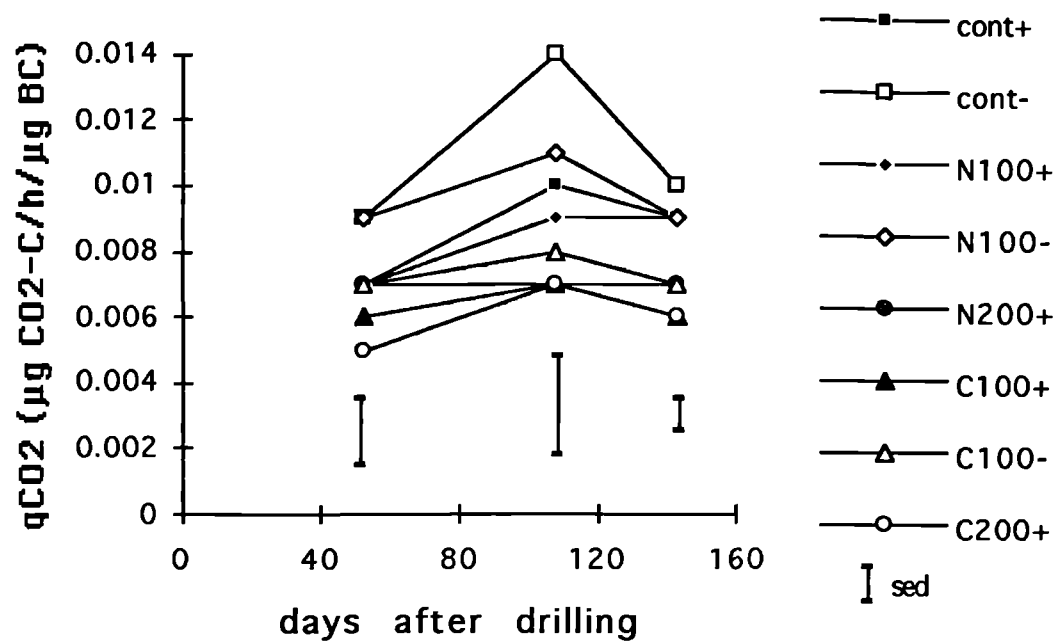


Figure 5.7 Microbial activity (qCO_2 ; $\mu g CO_2-C.h^{-1}.\mu g BC^{-1}$) in the 1994 Field A experiment

Table 5.4 Maize leaf area index (LAI; m^2 leaf area. m^{-2} ground area) in the 1994 Field A experiment

1994	28 Jul (1st DGA)		13 Sep (2nd DGA)	
treatment	LAI [‡]	log LAI	LAI [‡]	log LAI
<i>cont+</i>	2.03	0.48	2.02	0.48
<i>cont-</i>	0.46	0.16	0.77	0.25
<i>N100+</i>	2.06	0.48	3.10	0.61
<i>N100-</i>	1.14	0.32	1.04	0.31
<i>N200+</i>	2.68	0.55	3.26	0.62
<i>C100+</i>	1.55	0.40	1.84	0.45
<i>C100-</i>	0.44	0.16	0.44	0.16
<i>C200+</i>	2.31	0.52	2.89	0.59
SED		0.060		0.045

[‡]statistical analysis carried out on logarithmically transformed data ($\log LAI$)

In both compost and Nitram plots, BC was highest at the higher rate of N application (C200+ and N200+; $p < 0.05$), but no such difference occurred in relation to BN.

An opposite pattern occurred in microbial activity ($q\text{CO}_2$, Figure 5.7) when compared with BC and BN. A general increase in $q\text{CO}_2$ in the second sampling was followed by a decrease in the third sampling. Control and Nitram plots had higher levels of microbial activity than compost ones throughout the experiment, particularly with weed competition (- herb). In the third sampling, compost plots had in general significantly lower microbial activity than control and Nitram ones, with and without herbicide application (+ and - herb, respectively; $p < 0.05$).

Microbial biomass C/N ratio ranged from 3.0 to 5.5 in all samplings (data not presented). A significant difference was found between the rates of N application at the second ($p < 0.05$) and third ($p < 0.01$) samplings, both C200+ and N200+ having higher C/N ratio (approximately 5.0-5.5) than C100+ and N100+ (approximately 3.0-4.0).

5.1.3.3 Maize Destructive Growth Analyses

Maize leaf area index and dry biomass production are presented in Tables 5.4 and 5.5, respectively. Results for fresh biomass production were consistent with these and are presented in Appendix 10.

Maize development was greatly affected by weed competition throughout the experiment (Plates 5.2 and 5.3). Plots with weed competition (- herb) had the lowest maize leaf area and biomass production on both samplings ($p < 0.001$), and among them C100- had significantly lower leaf area than N100- ($p < 0.05$). Without weed competition (+ herb), no significant differences were found between N100+, N200+ and C200+, but maize had lower leaf area and dry matter production on control and C100+ plots on the second sampling ($p < 0.01$). A significant interaction was found in September between the type of fertiliser and the rates of application, maize dry matter production having a higher increase from 100 to 200 kg N.ha⁻¹ in compost than in Nitram plots ($p < 0.05$).

Table 5.5 Maize dry matter production (g.m⁻²) in 1994 Field A experiment

1994	28 Jul (1st DGA)		13 Sep (2nd DGA)	
treatment	dry weight [‡]	log dry weight	dry weight [‡]	log dry weight
<i>cont+</i>	172	2.23	700	2.84
<i>cont-</i>	27	1.39	80	1.88
<i>N100+</i>	177	2.23	952	2.97
<i>N100-</i>	75	1.84	123	2.08
<i>N200+</i>	235	2.31	1082	3.03
<i>C100+</i>	117	2.05	565	2.74
<i>C100-</i>	30	1.46	53	1.71
<i>C200+</i>	198	2.29	1125	3.04
SED		0.135		0.084

[‡]statistical analysis carried out on logarithmically transformed data (*log dry weight*)

5.1.3.4 Maize harvest

Maize fresh (Figure 5.8) and dry matter yields (Figure 5.9) were significantly lower in plots without weed control (- herb; $p < 0.001$), similarly to the results obtained in the DGAs (Section 5.1.3.3). Yields were much lower than the average expected for the region with the cultivar used (Section 3.1, Chapter 3). Maize dry matter content (DM) averaged 26% with and without herbicide application, ranging from 23% in *C100+* and *N100-* to 27% in *N100+*, *N200+* and *C200+* ($p < 0.05$). An interaction was found between the type of fertiliser and the rates of application, as maize DM was higher in compost at 200 than at 100 kg N.ha⁻¹, but remained constant in Nitram at both rates ($p < 0.05$).

In general, Nitram-treated maize had higher fresh and dry matter yields than with compost at equivalent N availability and herbicide application ($p < 0.05$). However, the differences were not significant at the higher level of N application (*N200+* and *C200+*). Yields tended to increase with increased rates of application of Nitram ($p < 0.05$) and compost ($p < 0.01$).

The feeding quality of the forage was expected to be very poor due to the low maize DM and the high level of weed infestation, and digestibility was not assessed. Cob expressed as percentage of dry matter averaged 57% without weed competition (+ herb) and only 9% in the presence of weeds (- herb; $p < 0.001$), but no significant differences were found between additives.

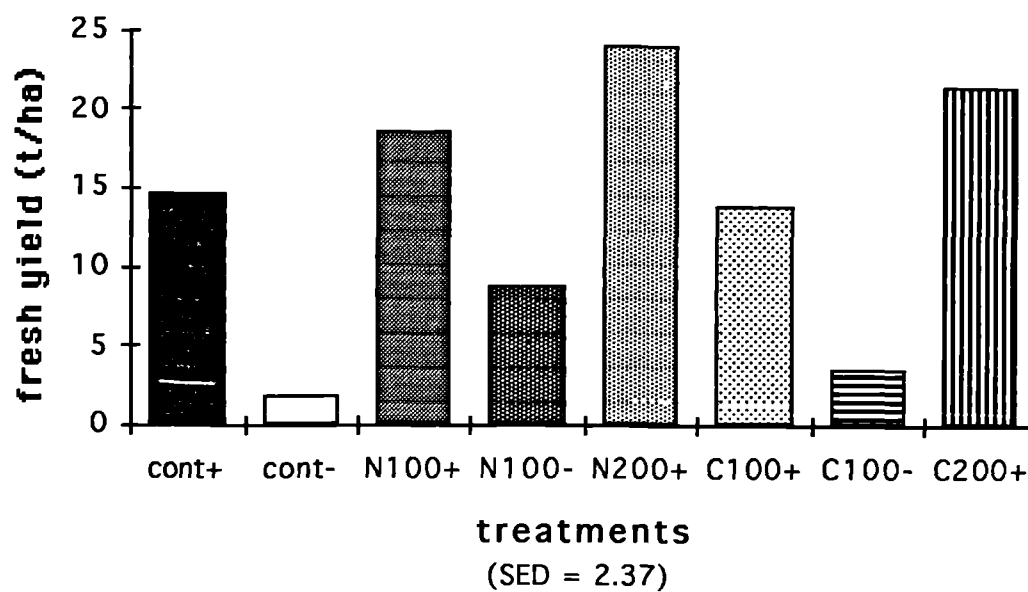


Figure 5.8 Maize fresh biomass yield ($\text{t}\cdot\text{ha}^{-1}$) in the 1994 Field A experiment

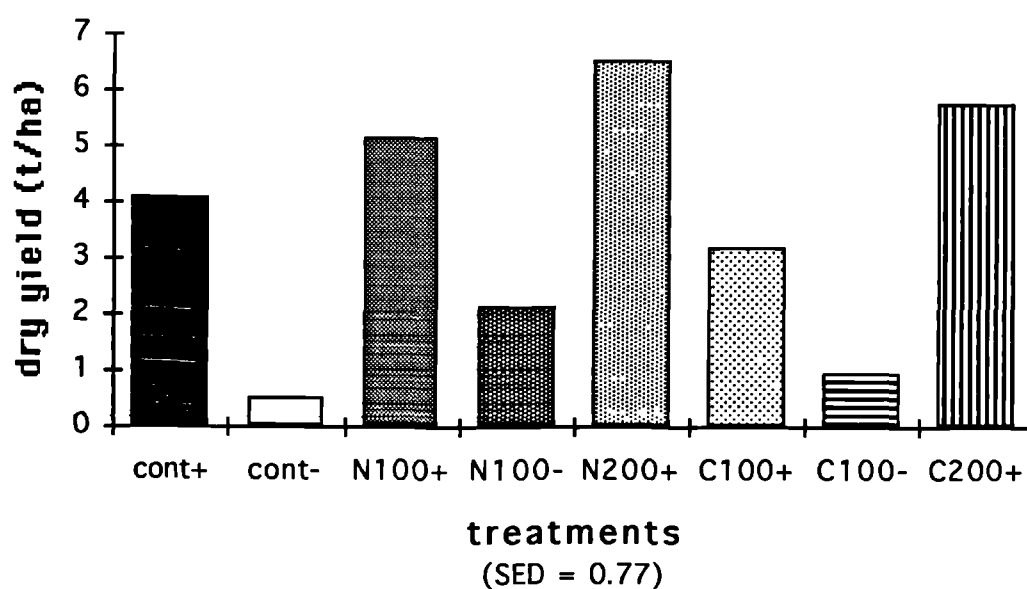


Figure 5.9 Maize dry matter yield ($\text{t}\cdot\text{ha}^{-1}$) in the 1994 Field A experiment

5.1.3.5 Maize nutrient uptake

Because of the high level of weed infestation in maize rows, and subsequently in the maize harvested, crop nutrient uptake was only determined in plots with weed control (+ herb).

Table 5.6 Maize total N, P, K, Ca and Mg uptake (kg.ha⁻¹) in the 1994 Field A experiment, in plots with weed control (+ herb)

treatment	N uptake	P uptake	K uptake	Ca uptake	Mg uptake
cont+	49.2	8.2	42.4	14.3	9.1
N100+	69.6	10.4	47.9	20.4	11.6
N200+	90.6	12.5	58.6	26.0	16.0
C100+	41.8	9.3	39.8	12.5	7.1
C200+	73.7	13.5	72.9	30.1	11.5
SED	11.25	1.43	8.60	8.60	1.59

In general, nutrient uptake was significantly higher with higher level of N application (200 kg N.ha⁻¹), particularly in compost-treated plots (Table 5.6; $p < 0.01$). Nitram-treated plots showed higher maize N and Mg uptake than compost ones, although the difference was only significant at the lower level of N application (N100+ and C100+; $p < 0.05$).

5.1.3.6 Weed analyses

Table 5.7 Weed dry biomass production (g.m⁻²) in the 1994 Field A experiment, in plots without weed control (- herb)

treatment - 1994	28 Jul (1st DGA)	13 Sep (2nd DGA)
cont-	400	360
N100-	498	392
C100-	438	368
SED	36.0	45.0

Weeds were only assessed in plots without weed control (- herb), because although there were weeds present in the + herb plots, any differences in results would be probably due to the uneven mechanical and manual weed control, and not to the treatments applied. Weed biomass tended to be

higher in Nitram-treated plots than in control and compost ones, being significantly higher in *N100-* than *cont-* in July ($p < 0.05$; Table 5.7). Weed species (Appendix 7) were randomly distributed in the field, and were not associated with particular treatments.

Weed nutrient uptake (Table 5.8) was generally higher in Nitram-treated plots than in control and compost ones, these differences being significant for N ($p < 0.01$) and Mg ($p < 0.05$) uptake.

Table 5.8 Weed total N, P, K, Ca and Mg uptake ($\text{kg} \cdot \text{ha}^{-1}$) in the 1994 Field A experiment, in plots without weed control (- herb)

treatment	N uptake	P uptake	K uptake	Ca uptake	Mg uptake
<i>cont-</i>	35.2	10.6	43.1	40.6	5.3
<i>N100-</i>	67.1	11.9	66.2	66.1	7.1
<i>C100-</i>	37.3	12.2	60.9	35.5	5.0
SED	5.23	1.28	9.74	16.67	0.73

5.1.4 Discussion

The application of compost clearly increased nutrient levels (total-N, extractable P, K, Mg) in soil, which appeared to be building up towards the end of the crop development, particularly at the higher level of application. These results were consistent with those reported by Pain (1978), Fraser *et al* (1988) and Sharpley and Smith (1995). The presence of only a few significant differences between compost and Nitram treatments was probably due to the high level of organic matter originally present in the soil. Whilst it is being decomposed, soil organic matter supplies the nutrients not contained in Nitram fertiliser in adequate quantities for maize development. The quantity of these appeared to be adequate even when maize was facing weed competition, as the lack of significant differences in these soil nutrients between + herb and - herb plots indicates.

On the other hand, nitrate levels were higher in Nitram-treated soil, suggesting that the supply of readily available N to the crop could be excessive with Nitram application, particularly at the higher rate. The lack of significant differences between the two rates of Nitram application without weed competition indicates that the higher rate was indeed excessive, as it

did not result in additional yields. Nitrate levels significantly decreased with weed competition, and weed biomass was higher in Nitram-treated plots, indicating that any excess of nitrate was being taken up by the weeds, thus increasing their growth. Moreover, as maize's nitrate uptake is minimal during the initial stages of crop development (Pain 1978; Fageria *et al* 1991), the excess of nitrate with Nitram application would tend to leach, causing pollution of the ground water table. In trials with the use of lysimeters, Ott (1990) found that the NO_3^- leaching potential of farmyard manure compost was only 61% of that of mineral fertiliser. Beauchamp (1983) reported that soils treated with mineral N contained about twice as much NO_3^- as those receiving organic fertiliser and thus had greater potential for leaching.

Compost applied at the higher rate still resulted in low levels of soil nitrate. Nevertheless, the lack of significant differences in maize yields and nutrient uptake between compost and Nitram at the higher rate of application indicates that the quantities of available nutrients (including N) supplied by compost were adequate for maize development. At the lower rate of application, the lower yields, lower nutrient uptake and lower dry matter content of compost-treated maize suggest that the quantities of N made available were not sufficient for crop development. This could be due to a slow mineralisation rate of compost N, as the equivalent rate of N, readily available in Nitram, resulted in adequate maize development. Moreover, short-term yield losses occurring when organic fertilisers start to be applied (replacing chemical ones) might result from microbial immobilisation of nutrients, as microbial biomass increases (Fauci and Dick 1994a).

Negligible levels of $\text{NH}_4\text{-N}$ were expected with soil pH around 8.0. Nitrification is rapid in alkaline arable soils, and thus nitrate dominates the mineral N component of these soils (Rochester *et al* 1992). Moreover, in soils with an alkaline reaction, any ammonium present may be lost through ammonia volatilisation (Hébert *et al* 1991).

The lower dry matter content of compost-treated soil in the second sampling, after a dry period, indicates a higher soil water content than in control and Nitram plots, most likely because of the capacity of compost to absorb and retain water and to improve soil physical properties, thus resulting in increased availability of water to the plant (Dalzell *et al* 1987; Metzger and Yaron 1987; Balashov 1996).

The lower uptake of Mg by compost-treated maize was probably due to the higher levels of K supplied by compost. As the K^+ ion competes with the Ca^{++} and Mg^{++} ions in plant uptake, high concentrations of potassium in soil from dairy manure compost application result in reduced Ca and Mg in the maize tissue (Tisdale and Nelson 1975; Brinton and Seekins 1994).

Weed competition proved highly detrimental to maize development, with much lower crop biomass production in plots without weed control. Even in plots with weed control, weed competition at the early stages of crop development, due to the failure of the herbicide, was enough to affect maize, resulting in low overall yields. Low temperatures after crop emergence (Appendix 9), further delaying the usually slow growth of maize at its early stages (Bunting 1978), and the high level of weed infestation in the field area used for the experiment, contributed to the below average results obtained.

Herbicide (clopyralid) application apparently did not affect microbial biomass. Wardle *et al* (1993) also found no consistent direct effects of herbicides on microbial biomass. Moreover, microorganisms appeared to be more competitive with weeds than maize was, as the lack of significant differences in biological assessments between plots with and without weed control indicates. The high content of soil native organic matter was probably being mineralised, microorganisms appearing more able to use these nutrients than plants. However, at the second sampling, during the peak of maize growth rate and N uptake (from flowering to early grain formation; Bunting 1978), a general decrease in microbial biomass and an increase in its activity indicated strong competition for nutrients with the crop. The pool size of microbial biomass and its respiratory activities can show temporal changes during crop development, and they are also influenced by climate and soil nutritional status (Ross *et al* 1995). Soil nutrients as a whole were at a lower level at the second sampling, thus confirming a higher maize nutrient uptake at that stage, resulting in higher competition between the crop and the microorganisms.

Microbial metabolic quotient (qCO_2) can be a good indicator for overall soil system status, reflecting ecological disturbance as microbial inefficiency (higher respiration per unit biomass) is greater in disturbed conditions (Visser and Parkinson 1992; Wardle *et al* 1993). In agricultural soils, a high metabolic quotient means that nutrient turnover happens with a high consumption of C (Insam *et al* 1991; Fauci and Dick 1994a). Compost-treated

plots had lower $q\text{CO}_2$ than Nitram and control ones, indicating lower nutrient competition conditions for microorganisms even at the peak of maize uptake. Humic acids extracted from composted manure are quite similar to humic acids originating from the soil (Deiana *et al* 1990), and after a certain age compost reaches a level of stability (C/N ratio around 10, Appendix 3) in which it will only slightly modify soil microbial activity (Jedidi *et al* 1993).

Both BC and BN tended to be higher in compost plots, probably due to its supply of C, a limiting nutrient for microbial biomass growth. Fauci and Dick (1994a) reported that inorganic N amendments had no significant short-term effect on microbial biomass C. However, the added N stimulates C inputs by increasing root and shoot growth and their exudates, suggesting an indirect effect of inorganic N on BC. This could explain why Nitram plots had lower metabolic quotient and higher BC at the higher rate of N application, as the extra nutrients supplied directly or indirectly (extra fertiliser reflecting in more plant material) reduced the effect of competition with maize and promoted biomass growth (Insam *et al* 1991).

However, although soil nitrate levels were higher in Nitram treated plots, the extra N available did not result in increased BN, and no significant differences were found in BN between the two rates of Nitram application. Relationships among soil microbial parameters and soil nitrogen levels may prove difficult to establish, due to the short-term fluctuations in soil fertility and biological properties. N. Gunapala and K. M. Scow (pers. comm.) reported a consistently significant negative relationship between microbial biomass and soil nitrate or ammonium levels. On the other hand, a strong positive correlation was found between most microbial parameters and potentially mineralisable N from an organic source. Results suggest that microorganisms make better use of N from an organic source than from a mineral N fertiliser. Fauci and Dick (1994b) reported that, in the long-term, inorganic N application resulted in significantly lower BN than in soils treated with organic amendments.

The overall increase in BC and BN from the second to the third samplings (the former coinciding with maize's flowering stage - GS 5.75, and the latter with its physiological maturity - GS 8.00; Groot *et al* 1986) was probably a result of decreased competition for nutrients between microorganisms and the crop. Moreover, the increase of shoot and rhizodepositions due to

senescence enriched the soil with organic nutrients that the microorganisms could use as substrate to produce biomass (Barber and Martin 1976). Similarly, the higher C/N ratio of the biomass in plots treated with higher level of N application was most likely to be due to the extra C added in the form of plant material.

Since microbial biomass acts as a source and a sink of nutrients to plants (Jenkinson and Ladd 1981; Visser and Parkinson 1992), increasing its size results in increasing the reservoir of nutrients, which will be made available to plants through decomposition/mineralisation processes. In other words, a larger pool of microbial biomass denotes a higher sustainability of soil fertility (Weil *et al* 1993).

5.1.5 Conclusions

Compost application can supply adequate levels of nutrients (N, P, K and Mg) for maize development with high yields, and can potentially sustain soil fertility by increasing microbial biomass.

Soil water holding capacity is increased with compost application, particularly in dry weather conditions.

Lower nitrate levels in compost-treated soil suggest slow mineralisation processes or N immobilisation in the microbial biomass, thus confirming the lower potential of compost for nitrate leaching and pollution.

The possibly slow mineralisation of organic N needs to be taken into account when choosing application rates of compost. Where mineralisation conditions are not ideal (e.g. temperate climate), lower levels of application can result in lower plant yields due to insufficient levels of available N.

Repeating the experiment in a warmer climate, with faster rates of mineralisation, would increase understanding of the effects of compost on soil fertility and maize production.

Maize development and yields are greatly reduced in the presence of weeds.

Microorganisms are less sensitive to weed competition than maize, their growth being not affected by the herbicide used, at least in the short-term.

At the peak of maize N uptake, the lower microbial biomass and the higher microbial activity indicates the stress due to nutrient competition, which was lower with compost than with Nitram application.

In contrast to maize and weed plants, microorganisms appear to make faster use of N from an organic source than in a readily available form.

Redrilling of this experiment will allow examination of compost effects in sustaining soil chemical and biological fertility (suggested by the higher nutrient and microbial biomass levels at the end of the crop development; Sections 5.1.3.1 and 5.1.3.2).



Plate 5.1 Inter-row brush weeder being used for mechanical weed control in the 1994 Field A experiment



Plate 5.2 Maize plots in the 1994 Field A experiment in July (1st DGA, overall growth reduced by early weed competition). Background - Field B.



Plate 5.3 Maize plots in the 1994 Field A experiment in September (2nd DGA, overall growth reduced by early weed competition).



Plate 5.4 Maize varieties *LG2080* (main plot to the left) and *Aziz* (main plot to the right) in a split-plot design in the 1994 Field B experiment

5.2 Field B - Effects of dairy manure compost on soil fertility, maize (*Zea mays* L.) maturity and maize production

5.2.1 Introduction

The results of the 1993 field experiment (Chapter 4) suggested a possible effect of compost in delaying the maturity of maize. This could be associated with a potential for higher productivity of compost-treated maize, as higher fresh biomass production could result in higher dry matter production if the plant had enough time to increase its dry matter content towards maturity. With this in mind, maize production was examined, comparing the cultivar used in 1993 with an earlier-maturing one.

Additionally, comparisons were made between compost and inorganic fertiliser as nutrient suppliers to maize, continuing research on the use of compost as an 'on-farm' produced fertiliser for sustainable maize production (Kiehl 1985; Dick and McCoy 1993). Accordingly, dairy manure and cereal straw were used again as the raw material to be composted.

Possible interactions within the soil-plant system between the two fertilisers and the two cultivars used were also examined.

5.2.1.1 Objectives

This experiment looked at the use of dairy manure compost in maize production, and studied its effects on soil nutritional status, crop nutrition and crop maturity in comparison with inorganic fertiliser.

5.2.2 Material and methods

A field experiment (named Field B) was conducted in *Orchard Field*, Wye College Estate (Chapter 3), in spring 1994, comparing inorganic N fertiliser (Nitram) and dairy manure compost. Two rates of application were used, 100 kg N.ha⁻¹, the recommended nitrogen fertilisation rate for commercial maize in the region, and half this amount (50 kg N.ha⁻¹).

The description of the general material and methods is given in Chapter 3. Before the start of the experiment, soil and compost samples were analysed

for nutrient content (Appendices 2 and 3, respectively). Previously, the area had grown a commercial oat crop.

Compost was uniformly spread on the soil surface and incorporated by power harrow (depth 10-15 cm) before drilling. Compost amounts were equivalent to Nitram ones in terms of N availability (Brinton 1985). Nitram was applied as topdressing in one application only, one week after drilling. Untreated controls (no fertiliser) were also included (Table 5.9).

As the effects of compost on weeds were not to be studied in this experiment, herbicide (atrazine) was sprayed in all plots for weed control, on the day of crop emergence.

Table 5.9 Additives used in 1994 Field B experiment

Additive	Description	Available N (kg.ha ⁻¹)
1. <i>cont</i>	untreated control + atrazine	0
2. <i>N50</i>	Nitram equivalent to 50 kg N.ha ⁻¹ + atraz	50
3. <i>N100</i>	Nitram equivalent to 100 kg N.ha ⁻¹ + atraz	100
4. <i>C50</i>	Compost (25 t.ha ⁻¹) equivalent to <i>N50</i> + atraz	50
5. <i>C100</i>	Compost (50 t.ha ⁻¹) equivalent to <i>N100</i> + atraz	100

A split-plot design was used, to allow for a comparison of all the treatments on two maize cultivars: *LG2080*, used in the 1993 field trial, and *Aziz*, an earlier-maturing cultivar (Figure 5.10; Plate 5.4). All five additives were fully randomised within each main plot, and four blocks were used, giving a total of 40 plots. Both cultivars of forage maize were drilled on the same day. The diary of operations is shown in Table 5.10.

Soil nutrient analyses (total N, NO₃⁻, NH₄⁺, extractable P, K, Ca, Mg, pH, dry matter and organic matter) were carried out (methods in Appendix 4). As there were no significant variations in time or treatment in soil Ca and pH in the 1993 field experiment, both determinations were only done at the first soil sampling. No soil biological assessments were made, as the effects of compost on microbial biomass and activity were not objectives of this experiment.

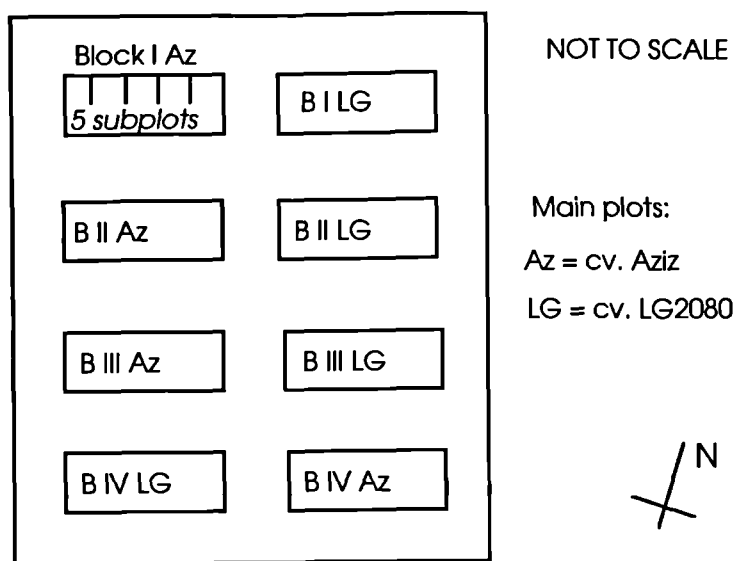


Figure 5.10 Layout of the 1994 Field B experiment

Table 5.10 Diary of operations in the 1994 Field B experiment

Date	Operation (inputs added where applicable)
April	Experiment area ploughed
25.04.94	Preliminary soil sampling for nutrient analyses
04.05.94	Compost spread on soil surface
05.05.94	Trial area power-harrowed (compost incorporated)
06.05.94	Forage maize (<i>cvs. LG2080 and Aziz</i>) drilled
13.05.94	Nitram applied as topdressing
19.05.94	Crop emergence (maize GS 1.00†)
	Atrazine sprayed in all plots
29.06.94	1st soil sampling for nutrient analyses (maize GS 2.50 - 5/6 leaves)
07.07.94	1st DGA (maize GS 3.25 - 8/9 leaves)
01.08.94	2nd soil sampling for nutrient analyses (maize GS 5.00 - flowering, start of pollen shedding)
03.08.94	2nd DGA (maize GS 5.00)
06.09.94	3rd DGA (maize GS 7.00 - early milk ripe)
22.09.94	3rd soil sampling for nutrient analyses (maize GS 8.00 - early dry ripe, physiological maturity)
05.10.94	Harvest (maize GS 8.25 - dry ripe)

†maize Growth Stage (Groot *et al* 1986; Appendix 1)

Maize samples (Destructive Growth Analysis - DGAs) were taken at three stages for fresh and dry biomass yields, leaf area index and nutrient analyses (N, P, K, Ca, Mg). Weeds, if present, were not sampled.

Final maize fresh and dry matter production per unit area and maize dry matter content were determined at harvest. Analyses of maize nutrient content (N, P, K, Ca, Mg) and forage digestibility were carried out on the dried samples.

All data were analysed with the Macintosh SuperAnova GLM program (Abacus Concepts 1989), using analysis of variance followed by orthogonal contrasts. Heterogeneity of variance of some of the data required logarithmic transformations before statistical analyses (Finney 1989).

5.2.3 Results

5.2.3.1 *Soil nutrient analyses*

In general, no significant differences in soil nutrient levels were found between the two main plots (cultivars *Aziz* and *LG2080*). Soil pH and Ca also showed no significant differences between additives, averaging 8.0 and 1407 mg.kg⁻¹, respectively. Soil NH₄-N levels were negligible in all subplots.

Soil total N levels (Table 5.11) were generally not significantly different between additives, but significant interactions occurred at the first sampling between the type of additive and its level of application ($p < 0.05$), and between the level of application and the maize cultivar ($p < 0.01$). Subplots with Nitram application had higher soil total N levels at the higher rate of application, whereas the opposite occurred with compost application. Additionally, plots with *Aziz* showed higher soil total N content at 100 kg N.ha⁻¹, whilst *LG2080* plots had higher soil total N levels at 50 kg N.ha⁻¹, particularly with compost application.

Soil NO₃-N data were logarithmically transformed for the statistical analysis, but as the conclusions did not vary from those obtained before transformation, only the raw data are presented (Table 5.12).

Table 5.11 Soil total-N levels (%) with forage maize cultivars *Aziz* and *LG2080* in the 1994 Field B experiment

1994	29 Jun (1st smpl)		1 Aug (2nd smpl)		22 Sep (3rd smpl)	
additives	<i>Aziz</i>	<i>LG2080</i>	<i>Aziz</i>	<i>LG2080</i>	<i>Aziz</i>	<i>LG2080</i>
<i>cont</i>	0.16	0.15	0.14	0.14	0.24	0.22
<i>N50</i>	0.13	0.15	0.17	0.14	0.23	0.23
<i>N100</i>	0.17	0.15	0.15	0.16	0.22	0.23
<i>C50</i>	0.15	0.16	0.14	0.15	0.23	0.24
<i>C100</i>	0.17	0.13	0.14	0.14	0.23	0.23
	<i>additive*</i>					
	<i>cultivar</i>	<i>within cv.</i>	<i>add*cv.</i>	<i>within cv.</i>	<i>add*cv.</i>	<i>within cv.</i>
SED	0.017	0.012	0.025	0.018	0.020	0.014

Table 5.12 Soil NO₃-N levels (mg.kg⁻¹) with forage maize cultivars *Aziz* and *LG2080* in the 1994 Field B experiment

1994	29 Jun (1st smpl)		1 Aug (2nd smpl)		22 Sep (3rd smpl)	
additives	<i>Aziz</i>	<i>LG2080</i>	<i>Aziz</i>	<i>LG2080</i>	<i>Aziz</i>	<i>LG2080</i>
<i>cont</i>	13.8	13.0	5.6	6.0	2.1	1.4
<i>N50</i>	27.8	26.3	12.6	14.5	7.2	1.8
<i>N100</i>	37.2	33.9	26.3	13.1	11.0	7.9
<i>C50</i>	17.4	17.7	7.5	7.2	6.5	1.6
<i>C100</i>	19.6	19.8	8.1	8.3	5.8	2.9
	<i>additive*</i>					
	<i>cultivar</i>	<i>within cv.</i>	<i>add*cv.</i>	<i>within cv.</i>	<i>add*cv.</i>	<i>within cv.</i>
SED	4.81	3.41	6.63	4.69	2.74	1.94

Prior to treatment application, soil NO₃-N was about 17.6 mg.kg⁻¹. Afterwards, levels were higher in Nitram-treated subplots than in compost and control ones at the three sampling dates ($p < 0.001$, $p < 0.01$ and $p < 0.05$, respectively), particularly at the higher rate of application. An interaction ($p < 0.05$) was found between type of fertiliser and rate of application, levels of nitrate increasing from the lower to the higher rate with Nitram application, but not significantly increasing with compost application.

No significant differences in soil organic matter content were found between additives in all samplings, although this ranged from 4.9% in control and Nitram plots to 5.2% in compost plots (mean of two cultivars). However,

plots planted with maize cultivar *Aziz* showed a higher soil organic matter content (5.3%; $p < 0.05$) than the ones planted with *LG2080* (4.9%) throughout the experiment.

Soil K data were logarithmically transformed for statistical analysis, and are presented in Table 5.13. Results from soil P and Mg analyses are presented in Table 5.14. In general, soil extractable P, K and Mg levels were higher in compost- than in control ($p < 0.05$) and Nitram-treated subplots ($p < 0.001$) throughout the experiment, particularly at the higher rate of application.

Table 5.13 Soil extractable K levels (mg.kg^{-1}) with forage maize cultivars *Aziz* and *LG2080* in the 1994 Field B experiment

1994 add	29 June (1st smpl)				1 Aug (2nd smpl)				22 Sep (3rd smpl)			
	<i>Aziz</i>		<i>LG2080</i>		<i>Aziz</i>		<i>LG2080</i>		<i>Aziz</i>		<i>LG2080</i>	
	K $\ddagger$	logK	K $\ddagger$	logK	K $\ddagger$	logK	K $\ddagger$	logK	K $\ddagger$	logK	K $\ddagger$	logK
<i>cont</i>	188	2.3	180	2.2	136	2.1	122	2.0	200	2.3	183	2.3
<i>N50</i>	229	2.3	188	2.2	136	2.1	74	1.7	208	2.3	191	2.3
<i>N100</i>	155	2.2	122	2.1	101	1.8	39	1.5	200	2.3	191	2.3
<i>C50</i>	287	2.4	295	2.5	211	2.3	115	2.1	323	2.5	282	2.4
<i>C100</i>	459	2.7	492	2.7	239	2.4	191	2.3	381	2.6	487	2.7
	<i>add*</i>		<i>same</i>		<i>add*</i>		<i>same</i>		<i>add*</i>		<i>same</i>	
	<i>cv.</i>		<i>cv.</i>		<i>cv.</i>		<i>cv.</i>		<i>cv.</i>		<i>cv.</i>	
SED	0.17		0.12		0.29		0.21		0.10		0.07	

$\ddagger$ statistical analysis of data carried out on logarithmically transformed data ($\log K$)

Interactions ($p < 0.01$) were found between the type of fertiliser and the rate of application in all nutrients, levels being higher at 100 than at 50 kg N.ha^{-1} in compost-treated subplots, but not being significantly different in Nitram ones between the two rates of application. Interactions also occurred between type and rate of fertiliser applied and the maize cultivar ($p < 0.05$). In general, nutrient levels had a higher increase from 50 to 100 kg N.ha^{-1} both in compost-treated subplots with cultivar *LG2080*, and in Nitram-treated subplots with *Aziz*. However, nutrient levels were lower at the higher rates of application in compost-treated subplots with cultivar *Aziz*, and in Nitram-treated subplots with *LG2080*.

Table 5.14 Soil extractable P and Mg levels (mg.kg⁻¹) with forage maize cultivars *Aziz* and *LG2080* in the 1994 Field B experiment

1994	29 June (1st smpl)				1 Aug (2nd smpl)				22 Sep (3rd smpl)			
	<i>Aziz</i>		<i>LG2080</i>		<i>Aziz</i>		<i>LG2080</i>		<i>Aziz</i>		<i>LG2080</i>	
add	P	Mg	P	Mg	P	Mg	P	Mg	P	Mg	P	Mg
<i>cont</i>	59.6	47.1	54.7	47.7	54.5	55.2	47.7	55.0	54.5	51.0	63.5	48.0
<i>N50</i>	55.3	49.8	63.4	49.1	49.8	59.6	46.7	57.1	56.9	50.6	64.6	48.1
<i>N100</i>	59.4	44.3	51.9	46.1	48.3	54.4	45.5	51.7	63.3	52.2	62.7	50.6
<i>C50</i>	66.6	55.6	63.6	55.4	54.1	66.4	50.8	52.3	68.0	61.1	63.1	53.5
<i>C100</i>	75.4	62.5	95.6	61.5	54.5	62.0	59.8	59.0	67.8	63.3	88.0	66.8
	<i>add*</i>	<i>add*</i>	<i>same</i>	<i>same</i>	<i>add*</i>	<i>add*</i>	<i>same</i>	<i>same</i>	<i>add*</i>	<i>add*</i>	<i>same</i>	<i>same</i>
	<i>cv.</i>	<i>cv.</i>	<i>cv.</i>	<i>cv.</i>	<i>cv.</i>	<i>cv.</i>	<i>cv.</i>	<i>cv.</i>	<i>cv.</i>	<i>cv.</i>	<i>cv.</i>	<i>cv.</i>
SED	9.99	5.10	7.06	3.61	6.18	7.23	4.37	5.11	10.13	5.58	7.16	3.95

Soil dry matter content (DM) was higher in Nitram-treated subplots, this being significant at the first sampling (averaging 82.5% for compost and 83.1% for Nitram; $p < 0.05$). Plots with cultivar *Aziz* tended to have lower DM than the ones with *LG2080*, although the difference was not significant (data not presented).

5.2.3.2 Maize Destructive Growth Analyses

Maize leaf area index (Table 5.15) and fresh biomass production (Appendix 10) showed results similar to those of dry matter production (Table 5.16). At the first sampling, subplots with compost application had larger leaf area and greater biomass production than those with Nitram application ($p < 0.05$).

In general, compost-treated subplots tended to show higher values at the higher rates of application with maize cultivar *LG2080*, whilst Nitram-treated subplots showed an increase in values from 50 to 100 kg N.ha⁻¹ with cultivar *Aziz*. Results from cultivar *LG2080* tended to be larger than those from *Aziz*, particularly at the last DGA ($p < 0.05$).

In September 1994, occurrence of common smut (*Ustilago maydis*) was detected in all plots planted with *LG2080*, but not in those planted with *Aziz*. Approximately 1% of plants were attacked in the ear shoot, in all *LG2080* plots, infection not being associated with particular additives.

Table 5.15 Maize leaf area index (LAI; m² leaf area.m⁻² ground area) with forage maize cultivars Aziz and LG2080 in the 1994 Field B experiment

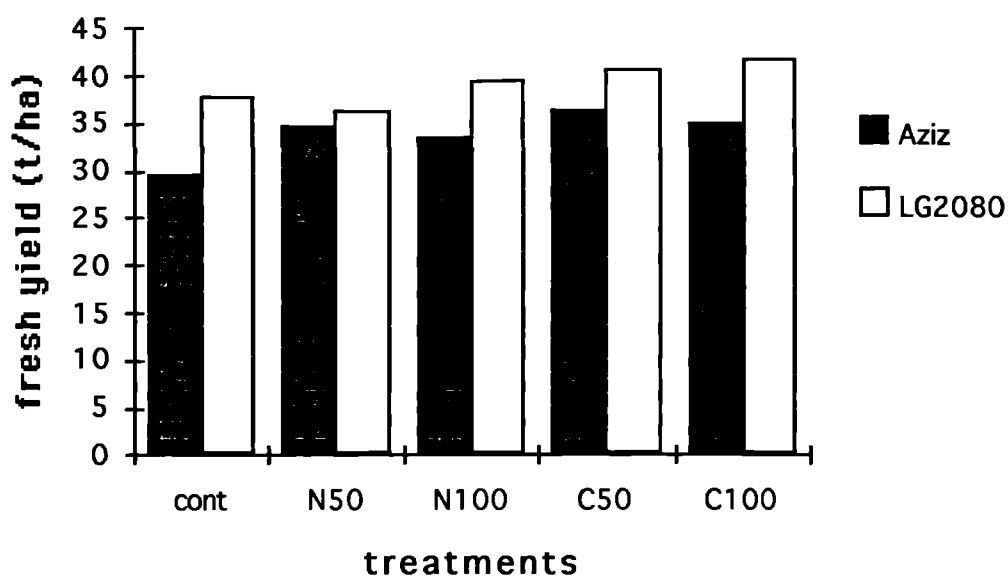
1994	7 Jul (1st DGA)		3 Aug (2nd DGA)		6 Sep (3rd DGA)	
additives	Aziz	LG2080	Aziz	LG2080	Aziz	LG2080
<i>cont</i>	2.09	1.47	5.65	5.68	4.62	4.76
<i>N50</i>	1.71	1.34	5.75	6.18	4.95	5.52
<i>N100</i>	1.64	1.37	5.14	6.68	5.07	6.00
<i>C50</i>	1.85	2.16	5.06	5.67	4.95	5.04
<i>C100</i>	1.62	1.80	5.73	6.54	4.93	5.98
	<i>additive*</i>					
	<i>cultivar</i>	<i>within cv.</i>	<i>add*cv.</i>	<i>within cv.</i>	<i>add*cv.</i>	<i>within cv.</i>
SED	0.391	0.276	0.743	0.525	0.747	0.528

Table 5.16 Maize dry matter production (g.m⁻²) with forage maize cultivars Aziz and LG2080 in the 1994 Field B experiment

1994	7 Jul (1st DGA)		3 Aug (2nd DGA)		6 Sep (3rd DGA)	
additives	Aziz	LG2080	Aziz	LG2080	Aziz	LG2080
<i>cont</i>	115	78	873	935	1760	1685
<i>N50</i>	85	72	863	963	1752	1765
<i>N100</i>	87	73	938	882	1727	1727
<i>C50</i>	95	110	873	875	1720	1872
<i>C100</i>	85	93	885	1028	1740	1958
	<i>additive*</i>					
	<i>cultivar</i>	<i>within cv.</i>	<i>add*cv.</i>	<i>within cv.</i>	<i>add*cv.</i>	<i>within cv.</i>
SED	19.2	14.1	131.2	92.9	235.3	166.0

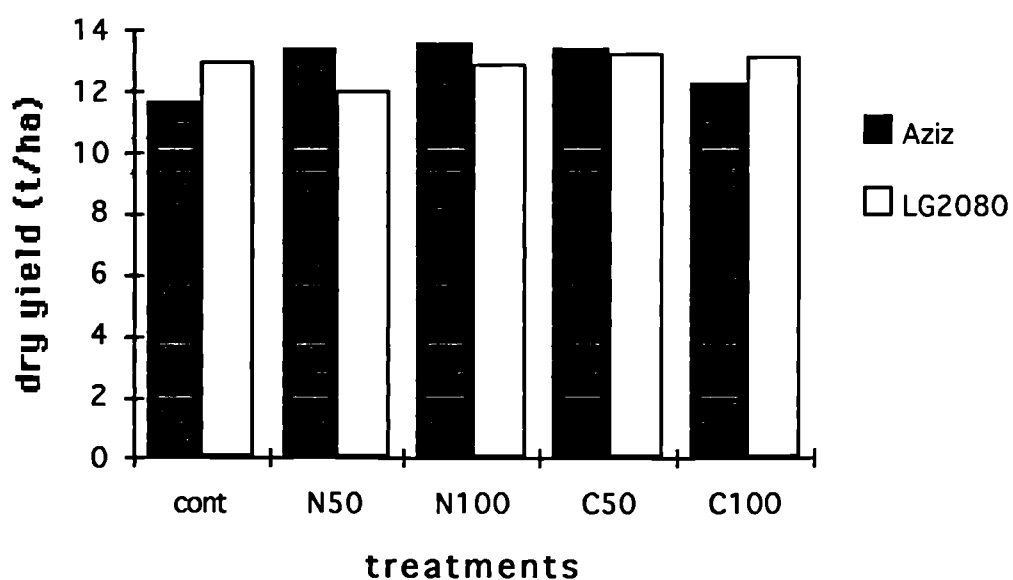
5.2.3.3 Maize harvest

Maize fresh biomass yield was higher in compost-treated subplots at both rates of application (Figure 5.11; $p < 0.01$), and higher in cultivar LG2080 than in Aziz with all additives, particularly at 100 kg N.ha⁻¹ ($p < 0.01$). A significant interaction occurred between the rate of application and the maize cultivar, the fresh yield being higher at the higher rate with cultivar LG2080, but higher at the lower rate with cultivar Aziz ($p < 0.05$).



(SED additive*cultivar = 1.70; same cultivar = 1.20)

Figure 5.11 Maize fresh biomass yield ($\text{t}\cdot\text{ha}^{-1}$) with forage maize cultivars *Aziz* and *LG2080* in the 1994 Field B experiment



(SED additive*cultivar = 0.78; same cultivar = 0.55)

Figure 5.12 Maize dry matter yield ($\text{t}\cdot\text{ha}^{-1}$) with forage maize cultivars *Aziz* and *LG2080* in the 1994 Field B experiment

Maize dry matter content at harvest averaged 33% and 38% in cultivars *LG2080* and *Aziz*, respectively ($p < 0.01$); and 34% and 36% in compost- and in Nitram-treated plots, respectively, the difference being greater at 100 kg N.ha⁻¹ ($p < 0.001$).

No significant differences were found in maize dry matter yield (Figure 5.12). However, significant interactions occurred between type of fertiliser and maize cultivar ($p < 0.05$), and between type and rate of fertiliser application ($p < 0.05$). Cultivar *Aziz* showed higher yields with Nitram application, whereas *LG2080* had better yields with compost. Additionally, dry matter yields were higher in subplots with the lower rates of compost application, and in subplots with the higher rates of Nitram application.

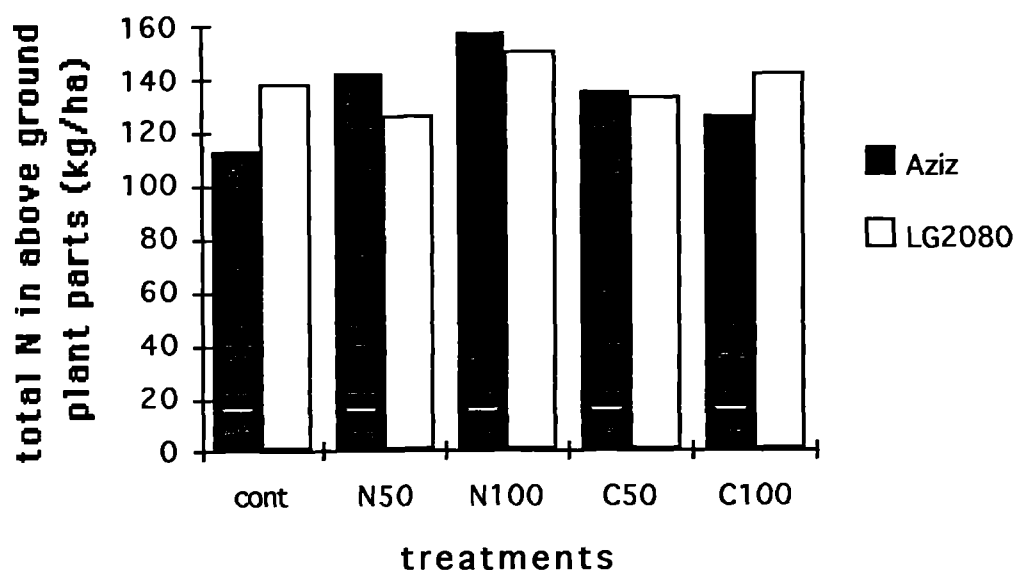
Cob expressed as percentage of dry matter averaged 44% in maize cultivar *LG2080*, and 50% in *Aziz* ($p < 0.05$), but there were no significant differences between additives. Forage maize digestibility was on average 71.5% with cultivar *Aziz*, and 72.5% with *LG2080*, no significant differences being found.

5.2.3.4 Maize nutrient uptake

Nitrogen uptake by maize is presented in Figure 5.13. Maize uptakes of P, K, Ca and Mg are presented in Table 5.17. Nitram-treated maize had significantly higher uptakes of N, Ca and Mg, particularly at 100 kg N.ha⁻¹ ($p < 0.001$), and with cultivar *Aziz* ($p < 0.05$).

In general, significant interactions occurred between type of fertiliser and maize cultivar ($p < 0.05$), with compost-treated maize showing a higher nutrient uptake with cultivar *LG2080*, and Nitram-treated maize showing a higher nutrient uptake with *Aziz*.

Maize showed a significantly higher accumulation of potassium with compost application than in control and Nitram subplots, both at the lower ($p < 0.05$) and at the higher rates of application ($p < 0.001$), especially with maize cultivar *LG2080*.



(SED additive*cultivar = 10.49; same cultivar = 7.42)

Figure 5.13 Maize total nitrogen uptake ($\text{kg}\cdot\text{ha}^{-1}$) with forage maize cultivars Aziz and LG2080 in the 1994 Field B experiment

Table 5.17 Maize total P, K, Ca and Mg uptake ($\text{kg}\cdot\text{ha}^{-1}$) with forage maize cultivars Aziz and LG2080 in the 1994 Field B experiment

1994 adds	Phosphorus		Potassium		Calcium		Magnesium	
	Aziz	LG2080	Aziz	LG2080	Aziz	LG2080	Aziz	LG2080
cont	17.5	23.6	93.0	118.2	33.8	31.1	24.2	27.2
N50	20.1	18.5	108.3	104.1	35.0	33.4	27.5	30.5
N100	23.1	21.6	102.8	102.4	38.1	35.3	31.9	31.6
C50	20.5	20.7	118.3	123.5	32.5	31.5	25.2	27.3
C100	19.5	22.6	117.8	135.1	28.3	31.6	23.2	27.7
	same		same		same		same	
	add*cv.	cv.	add*cv.	cv.	add*cv.	cv.	add*cv.	cv.
SED	2.13	1.51	10.96	7.75	3.56	2.52	3.09	2.19

Uptakes of N, P, Ca and Mg tended to be higher at the higher rate of application, particularly with Nitram application, this difference being significant in N and P uptakes ($p < 0.01$). However, with cultivar *Aziz*, uptake of any nutrient (including K) by compost-treated maize tended to decrease from 50 to 100 kg N.ha⁻¹, although no significant differences were found.

5.2.4 Discussion

The higher levels of nitrate in soils with Nitram application resulted in higher maize N uptake. However, this was not associated with higher productivity, as no differences were found in maize dry matter yields between Nitram and compost additives. The excess of nitrate in the soil would tend to leach, particularly after the growing season, eventually reaching the ground water. The higher the soil nitrate content after crop removal, the higher its leaching potential (Magdoff 1991; Maynard 1993). The fact that nitrate content increased with increasing rates of application of Nitram, but not of compost, would further denote the lower pollution potential of the latter.

The absence of NH₄-N in soil was probably due to the high soil pH, with optimum conditions for mineralisation rather than ammonification processes (Rochester *et al* 1992).

Despite the high levels of native organic matter in soil, which would tend to mask any treatment effect due to its own nutrients' mineralisation, compost application still resulted in higher soil nutrient levels, especially P, K and Mg, and soil organic matter content. The levels increased towards the end of the crop's development, especially with the higher rate of application, suggesting that nutrients and organic matter would be building up in soil treated with compost. This would indicate a sustained soil fertility in the long-term, being particularly important in soils with originally lower nutrient and organic matter contents (Hornick and Parr 1987).

The particularly high K content of dairy manure compost resulted in high soil K levels (Kiehl 1985). When potassium supply is abundant, a 'luxury consumption' often occurs, which can interfere with the uptake and physiological availability of Ca and Mg ions (Marschner 1986). Potassium levels were indeed high in the tissue of compost-treated maize, this probably being the cause for the lower levels of Ca and Mg in the plant, despite the

high levels in the soil. According to Pain (1978), the sum of K, Ca and Mg percentages is generally constant in a plant at all growth stages, and high rates of K can result in low levels of Ca and Mg.

The higher soil water content (lower dry matter content) in compost-treated soils could result in better yields under drought conditions, by increasing water availability to plants (Dalzell *et al* 1987). The higher soil water content with cultivar *Aziz* was probably due to the overall higher soil organic matter content found in plots with this cultivar than with *LG2080*. This difference in soil organic matter levels between plots could be due to field area patterns, as it is unlikely that maize cultivars could influence OM levels, particularly considering the short duration of this experiment.

In general, cultivar *Aziz* responded better to Nitram application, showing increases in soil nutrient levels, maize yields and nutrient uptake with increasing rates of N.ha^{-1} . An opposite pattern occurred with compost application on the same maize cultivar: the higher the rate, the lower the responses. On the other hand, cultivar *LG2080* showed better responses to compost than to Nitram at both rates of application. The higher levels of organic matter content found in plots with cultivar *Aziz* might also partly explain its lower responses to compost application than cultivar *LG2080*, due to the high levels of organic nutrients already present in soil.

The occurrence of *Ustilago maydis* was probably due to favourable weather conditions for the germination of spores and development of fungus already present in soil (Cook 1978), and had no relation with the additives used in the area. The infection levels were low, and did not affect maize yields. Nevertheless, cultivar *LG2080* appeared to be more susceptible/less tolerant to its infection than did cultivar *Aziz*, and in areas with high occurrence of common smut, *LG2080* would not be recommended.

Maize leaf area and biomass production were higher under compost application, particularly with cultivar *LG2080*. However, due to the lower dry matter content (DM) of the maize, no significant differences were found in the final dry yields between compost and Nitram additives. Lower DM suggests a delayed maturity of the maize plant with compost application. This could be due to the higher potassium accumulation in compost-treated maize. Plants well supplied with potassium show increased uptake of water and reduced water loss, as potassium directly regulates stomatal

movements, a major mechanism in controlling the water regime of higher plants. Potassium is also the predominant osmotic solute in the vacuole, maintaining a high water level in the plant tissue even under drought conditions (Marschner 1986; Mengel and Kirkby 1987). The higher fresh yields could also be related to the higher soil water content, thus higher plant water availability in compost-treated soil (Metzger and Yaron 1987).

The apparent late maturity with compost application might also be explained by a direct action of humic molecules in the absorption of nutrients by plants, as low molecular weight humic molecules of compost can increase passive membrane permeability to protons. Thus, maturity would be delayed due to the higher plant capacity of absorbing nutrients over a longer period of time (Varanini *et al* 1993).

The lower fresh biomass yields and higher DM of maize cultivar *Aziz* at harvest, as well as a higher percentage of cob in its dry matter, confirms its earlier maturity in relation to cultivar *LG2080*. Nevertheless, although maize reached maturity with high DM levels, thus with clearly enough time for achieving its full productive potential, dry matter yields with compost application were not higher than with Nitram, particularly with cultivar *Aziz*.

Results indicate that cultivar *Aziz* performs better with chemical than with organic fertilisers. It has probably been selected for high input agriculture, requiring high levels of readily available N to reach its full yield potential. The use of an earlier variety other than *Aziz*, selected for low-input environments, might show a correlation between higher fresh and dry matter yields, i.e. a higher potential for crop productivity under compost application. Plant breeding programmes should attempt to develop varieties better adapted to low-input farming system, which would be able to reach high yields without requiring high nutrient availability (Ramirez 1982; Atlin and Frey 1989).

5.2.5 Conclusions

Results confirm the lower nitrate leaching potential using compost instead of mineral N fertilisers.

The higher nutrient levels in compost-treated soil at the end of the growing season indicates the long term ability of compost in sustaining soil fertility.

The use of compost is particularly recommended in areas of originally low soil fertility, with low organic matter content, and under drought conditions.

Maize fertilised with compost can reach dry matter yields equivalent to those obtained with mineral N fertilisers.

The breeding of plant cultivars adapted to low-input farming systems is crucial to ensure high yields in sustainable crop production.

Experiments in areas with a larger growing season, or using an earlier cultivar other than *Aziz* that responded better to organic fertilisers, might result in higher maize dry matter production correlated with the higher fresh biomass yields obtained under compost application.

Chapter 6. The 1995 Field Experiments

6.1 Cumulative effects of dairy manure compost on soil fertility, maize (*Zea mays* L.) production and weed growth, with comparisons of results under different climatic conditions

6.1.1 Introduction

Results of the 1994 Field A experiment (Chapter 5) suggested that compost application could sustain soil chemical and biological fertility, with higher nutrient and microbial biomass levels in soil at the end of the crop development. Thus, field experiments were carried out in 1995 to study the effects of cumulative application of dairy manure compost on soil fertility and on maize nutrition and production.

Compost nutrients are gradually and steadily used by soil microorganisms and made available to plants. Hence, soil capacity to supply nutrients to the crop is sustained, with reduced nutrient runoff (Vogtmann 1984; Lockeretz 1988). Compost application tends to increase the yield of crops in succeeding years because it has a greater residual effect on soil fertility than do mineral fertilisers (Parr and Colacicco 1987; Eghball *et al* 1995; Sharpley and Smith 1995).

Microbial-mediated processes are faster in warmer than in temperate climates because of higher temperature and moisture, usually resulting in lower native soil organic matter and nutrient levels in warmer regions (Hornick and Parr 1987). However, mineralisation of compost nutrients and the turnover of microbial biomass are also accelerated (Wardle 1992), leading to a greater availability of compost nutrients. Therefore, plants benefit more from compost application in warmer than in temperate conditions, resulting in higher nutrient uptake and crop yields even in the short-term (Dick and McCoy 1993).

In order to examine the effects of successive compost application on soil and crop, the 1994 Field A experiment was redrilled on the same plots. The same additives and methodology were used in an adjacent area, which was drilled

in 1995 only. Hence, it allowed comparisons of possible compost effects on soil and crop after one year and cumulatively after two years of application.

Additionally, an experiment with similar methodology was conducted by Sara Marinari, from the Department of Agrobiology and Agrochemistry at the *Università degli Studi della Tuscia*, in Viterbo, Italy, to investigate the effects of the use of compost in conditions of faster mineralisation, with warmer climate and lower original soil organic matter content.

It was thus intended that comparison of the results of these experiments would allow better understanding of the effects of dairy manure compost on soil chemical and biological fertility, maize nutrition and crop production.

The possible interactions within the soil-plant system were also observed in relation to nutrient supply, with and without the presence of weeds, comparing the results after both one year and two years of compost application.

6.1.1.1 Objectives

The objectives were to examine further the value of dairy manure compost as a fertiliser for sustainable maize production, comparing its effects on soil and crop with those of mineral fertiliser:

- a) after one year and cumulatively after two years of application;
- b) in temperate and in warmer climatic conditions.

6.1.2 Material and methods

Two randomised complete block experiments were carried out in 1995 to compare fertiliser effects after one and two years of application. Hence, the 1994 Field A experiment (Chapter 5) was redrilled in *Orchard Field*, Wye College Estate. This experiment with two successive fertiliser applications (1994 and 1995) was named *Field 2 years*. The new adjacent experiment, carried out only in 1995, was named *Field 1 year*, and had been under commercial spring barley in 1994.

A description of general material and methods is found in Chapter 3. Soil and compost (produced from dairy manure and cereal straw) were sampled for nutrient analyses prior to treatment application (Appendices 2 and 3,

respectively). Soil samples were taken from three blocks in both experiments. This preliminary analysis in *Field 2 years* allowed the determination of any residual effects from the previous year experiment (1994 Field A) in soil nutrient levels.

Compost was again compared with inorganic N fertiliser (Nitram), their amounts being equivalent in terms of nitrogen availability (Brinton 1985; Brinton and Seekins 1994). The same rates of application from the 1994 Field A experiment were used: 100 kg N.ha⁻¹ (the recommended N fertilisation rate for commercial maize in the Wye region) and 200 kg N.ha⁻¹ (the recommended rate in Viterbo, Italy, where a similar experiment for comparison was conducted in 1995 - described in this Section).

Table 6.1 Treatments used in the 1995 field experiments

Treatment	Description	Available N (kg.ha ⁻¹)	Weed control
1. <i>cont+</i>	untreated control with (+) herbicide	0	yes
2. <i>cont-</i>	untreated control without (-) herbicide	0	no
3. <i>N100+</i>	Nitram equiv. to 100 kg N.ha ⁻¹ + herb	100	yes
4. <i>N100-</i>	Nitram equiv. to 100 kg N.ha ⁻¹ - herb	100	no
5. <i>N200+</i>	Nitram equiv. to 200 kg N.ha ⁻¹ + herb	200	yes
6. <i>C100+</i>	Compost (50 t.ha ⁻¹) equiv. to <i>N100</i> + herb	100	yes
7. <i>C100-</i>	Compost (50 t.ha ⁻¹) equiv. to <i>N100</i> - herb	100	no
8. <i>C200+</i>	Compost (100 t.ha ⁻¹) equiv. to <i>N200</i> + herb	200	yes

Untreated controls (no fertiliser; Table 6.1) were included. Herbicide was used for weed control in five of the treatments, while three were left unsprayed for comparison. As clopyralid, the herbicide applied in 1994, failed to control the weeds, atrazine was used in 1995.

All treatments were fully randomised within each block of each experiment. Four blocks were used, giving a total of 32 plots in each experiment (Figure 6.1). A diary of operations is presented in Table 6.2.

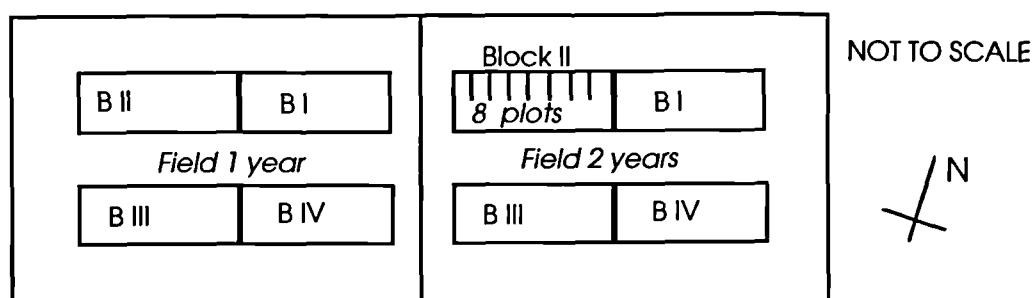


Figure 6.1 Layout of the 1995 field experiments

Table 6.2 Diary of operations in the 1995 field experiments

Date	Operation (inputs added where applicable)
April	Experiment areas ploughed
24.04.95	Preliminary soil sampling for nutrient analyses
25.04.95	Compost spread on soil surface
26.04.95	Experiment areas power-harrowed (compost incorporated)
27.04.95	Forage maize (<i>cv. LG2080</i>) drilled
03.05.95	Nitram applied as topdressing
08.05.95	Crop emergence (maize GS 1.00†)
15.05.95	Atrazine sprayed (maize GS 1.25 - 1 leaf)
19.06.95	1st soil sampling for nutrient and biological (<i>Field 2 years only</i>) analyses (maize GS 1.75 - 2/3 leaves)
10.07.95	1st DGA (maize GS 3.25 - 8/9 leaves)
31.07.95	2nd soil sampling for nutrient and biological (<i>Field 2 years only</i>) analyses (maize GS 5.25 - flowering, pollen shedding)
08.08.95	2nd DGA (maize GS 5.75 - end of flowering)
25.08.95	3rd DGA (maize GS 7.75 - late milk ripe)
28.08.95	3rd soil sampling for nutrient and biological (<i>Field 2 years only</i>) analyses (maize GS 8.00 - early dry ripe, physiological maturity)
06.09.95	Harvest (maize GS 8.25 - dry ripe)

†maize Growth Stage (Groot *et al* 1986; Appendix 1)

Soil nutrient analyses (total N, NO_3^- , NH_4^+ , extractable P, K, Ca, Mg, pH, dry matter and organic matter) were carried out at Wye College (methods in Appendix 4) from all plots of three blocks in each experiment. Soil Ca and pH were only analysed at the first soil sampling, as they did not vary significantly either with time or with treatment in the 1993 field experiment.

Only three treatments from three blocks in *Field 2 years* were sampled for biological assessments (C and N microbial biomass - BC and BN, and microbial activity - $q\text{CO}_2$), due to time and technical constraints. These treatments were *cont+*, *N200+* and *C200+*, which had showed higher treatment effects in the 1994 Field A experiment (Chapter 5). Samples were sent to *Università degli Studi della Tuscia*, in Viterbo, Italy, for analyses using the Fumigation-Extraction method (Appendix 6).

Maize samples (Destructive Growth Analysis - DGAs) were taken at three stages for determination of fresh and dry biomass and nutrient content (N, P, K, Ca, Mg). No leaf area index measurements were made, as results from the 1993 and 1994 experiments were consistent with those of maize biomass production. Plots were sampled at both their extremes, as described in Chapter 3. Weeds were also sampled in the DGAs, from the plots without weed control only (- herb), for dry biomass and nutrient content. Weed species present were the same as in the 1993 and 1994 field experiments, and are listed in Appendix 7. Final maize fresh and dry matter production per unit area were determined at harvest. Subsequently, maize nutrient uptake (N, P, K, Ca, Mg) and forage digestibility were also determined.

By the end of August, some maize plants had been knocked down and their cobs eaten, possibly by hares. The attack was concentrated at the North-Eastern side of *Field 2 years* (Figure 6.1), affecting plots *C200+* which had been placed at random on that edge of both Blocks I and IV. Approximately 50% of the maize plants on those plots were destroyed.

An experiment with the same fertilisers was conducted simultaneously by the *Università degli Studi della Tuscia* in Viterbo, Italy, in 1995 only, to examine the effects of compost application on soil and on maize production in conditions of a warmer climate and lower soil organic matter content. The methodology used was similar to that in Wye with one year of application only, but some modifications were needed. A forage maize cultivar adapted to Italian conditions was used, *Winner*, with similar characteristics to *LG2080* and with potential dry matter yield of 15-18 t.ha⁻¹. Weed control was carried out manually, as atrazine use was restricted in Italy. Maize was drilled on 17 May and harvested on 30 September 1995.

Meteorological data in Viterbo and in Wye are presented in Appendix 9. Soil samples were taken approximately at the same stages of maize development in both countries, to allow comparison of results. No soil nutrient analyses or maize DGAs were carried out in Viterbo, due to technical constraints. Therefore, comparisons with the *Field 2 years* in Wye were only possible in relation to soil biological assessments and maize final dry matter production.

Data from all three experiments were analysed separately with the Macintosh SuperAnova GLM program (Abacus Concepts 1989), using analysis of variance followed by orthogonal contrasts. Some of the data were logarithmically transformed for the analysis of variance because of heterogeneity of variance (Finney 1989). Comparisons between *Field 1 year* and *2 years* experiments were made using an independent *t*-test on the differences between selected treatments (Mead and Curnow 1983).

6.1.3 Results

6.1.3.1 Soil nutrient analyses

Table 6.3 Soil total-N % (Kjeldahl) in the 1995 *Field 1 year* and *2 years* experiments in Wye (24 Apr is preliminary sampling in *Field 2 years*)

1995	24 Apr	19 Jun (1st smpl)		31 Jul (2nd smpl)		28 Aug (3rd smpl)	
treat	<i>2 years</i>	<i>1 year</i>	<i>2 years</i>	<i>1 year</i>	<i>2 years</i>	<i>1 year</i>	<i>2 years</i>
<i>cont+</i>	0.19	0.21	0.19	0.18	0.18	0.17	0.16
<i>cont-</i>	0.20	0.20	0.18	0.19	0.17	0.16	0.15
<i>N100+</i>	0.18	0.20	0.17	0.19	0.17	0.17	0.16
<i>N100-</i>	0.20	0.20	0.18	0.19	0.16	0.16	0.16
<i>N200+</i>	0.20	0.22	0.20	0.19	0.18	0.16	0.16
<i>C100+</i>	0.19	0.21	0.20	0.18	0.18	0.16	0.15
<i>C100-</i>	0.21	0.22	0.17	0.19	0.18	0.16	0.16
<i>C200+</i>	0.19	0.22	0.20	0.19	0.18	0.17	0.17
SED	0.016	0.013	0.013	0.016	0.016	0.017	0.015

Soil pH averaged 8.0 in both experiments in Wye. Soil organic matter content (OM) ranged from 4.2 to 4.7% in *Field 1 year*. In *Field 2 years* (redrilled), values ranged from 4.2 to 4.8% in the preliminary soil sampling, and from 4.2 to 5.0% after treatment application, being higher than in *Field 1*

year in compost-treated soils. Additionally, compost-treated plots tended to have higher soil OM than Nitram and control throughout the samplings, especially at the higher rate of application, this difference being significant towards the end of the *Field 2 years* experiment ($p < 0.05$).

In Viterbo, soil pH averaged 7.0, and OM content was low, averaging 1.0-1.5%. No individual plot analyses were done, thus possible treatment differences could not be determined.

In general, no significant differences were found in soil total N levels between treatments in both field experiments (Table 6.3), although compost-treated plots tended to show higher levels, *C100+* being significantly higher than *N100+* at the 1st sampling in *Field 2 years* (redrilled; $p < 0.05$).

Soil $\text{NO}_3\text{-N}$ levels averaged 5.9 mg.kg^{-1} prior to treatment application in *Field 1 year*. They were higher in plots without weed competition (+ herb) at both second and third samplings in *Field 1 year* (Figure 6.2; $p < 0.05$ and $p < 0.01$, respectively) and in *Field 2 years* (Figure 6.3; $p < 0.001$).

Nitram-treated soil had the highest nitrate levels from the first to the third soil samplings in *Field 1 year* ($p < 0.001$, $p < 0.01$ and $p < 0.001$, respectively) and in *Field 2 years* ($p < 0.001$, $p < 0.01$ and $p < 0.01$, respectively), particularly at 200 kg N.ha^{-1} . Although nitrate levels tended to be higher at 200 kg N.ha^{-1} than at 100 kg N.ha^{-1} in Nitram-treated plots, especially at the first sampling ($p < 0.05$), they did not differ between the two rates of application in compost-treated plots. *Field 2 years* (redrilled) had higher nitrate levels than did *Field 1 year* in plots receiving Nitram ($p < 0.05$) or compost ($p < 0.01$), at the first and second samplings. Soil $\text{NH}_4\text{-N}$ levels were consistently negligible in both experiments.

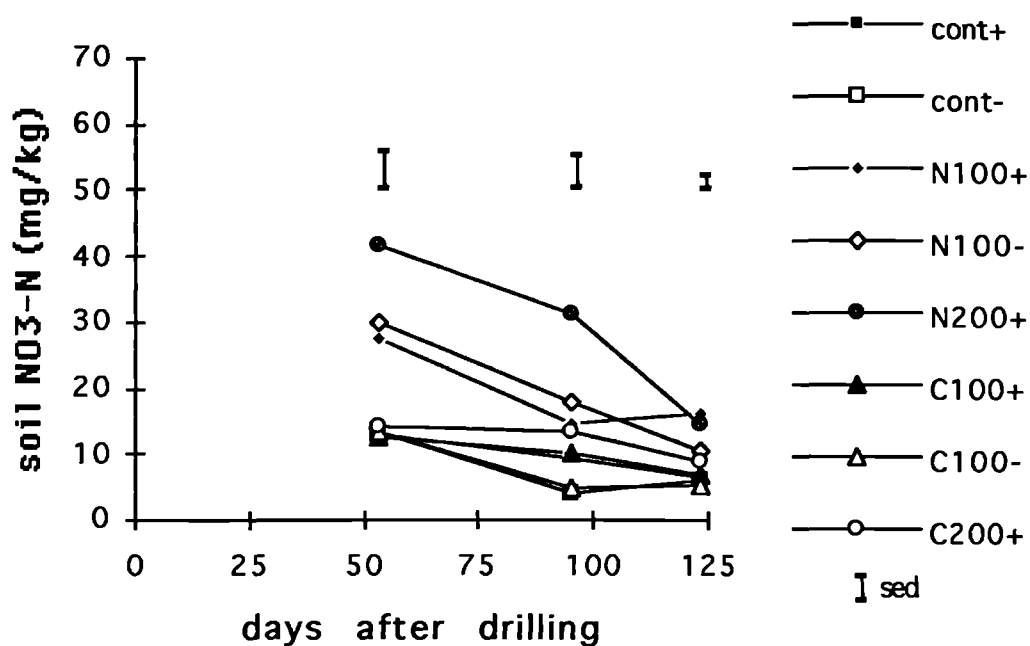
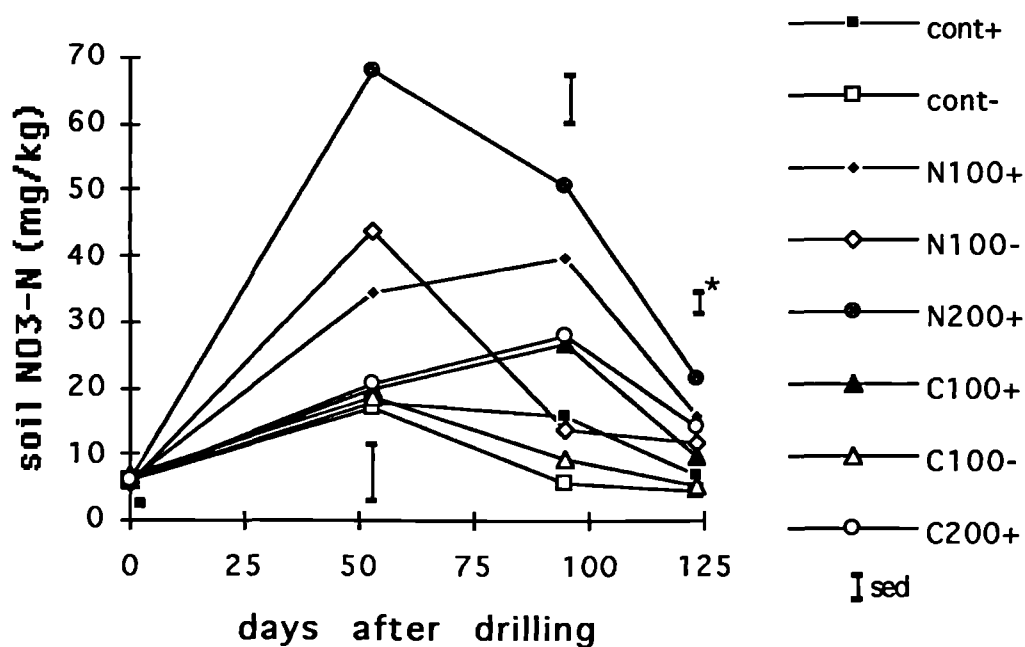


Figure 6.2 Soil nitrate levels (mg.kg⁻¹) in the 1995 *Field 1 year* experiment



* statistical analysis carried out on logarithmically transformed data

Figure 6.3 Soil nitrate levels (mg.kg⁻¹) in the 1995 *Field 2 years* experiment

Table 6.4 Soil extractable P levels (mg.kg⁻¹) in the 1995 *Field 1 year* and 2 *years* experiments in Wye (24 Apr is preliminary sampling in *Field 2 years*)

1995	24 Apr	19 Jun (1st smpl)		31 Jul (2nd smpl)		28 Aug (3rd smpl)	
treat	2 years	1 year	2 years	1 year	2 years	1 year	2 years
cont+	42.1	35.8	37.4	49.6	67.9	28.1	51.5
cont-	45.3	52.5	39.4	52.3	79.0	38.7	45.4
N100+	39.1	54.1	42.2	50.3	68.6	39.6	46.3
N100-	35.6	28.5	36.2	52.8	74.3	34.4	58.5
N200+	40.4	43.9	31.0	53.1	70.9	34.4	52.9
C100+	45.5	51.0	47.0	61.6	81.2	26.3	70.2
C100-	50.3	63.4	51.2	55.6	90.1	31.9	61.8
C200+	53.7	58.6	68.7	80.1	108.9	38.7	84.0
SED	6.94	9.67	6.08	5.58	9.09	8.04	9.39

The levels of soil extractable P (Table 6.4), K (Table 6.5) and Mg (Table 6.6) were highest in compost-treated plots in both experiments. This difference was particularly significant at 200 kg N.ha⁻¹, C200+ tending to have higher P ($p<0.001$), K ($p<0.001$) and Mg ($p<0.05$) levels than N200+ in all samplings (including the one prior to the consecutive treatment application in *Field 2 years* experiment). In general, K levels were also significantly higher in compost- than in Nitram-treated soil at 100 kg N.ha⁻¹ in both *Field 1 year* ($p<0.05$) and *Field 2 years* (redrilled; $p<0.001$).

An interaction occurred between type and rate of fertiliser application, C200+ tending to have higher P ($p<0.01$), K ($p<0.05$) and Mg ($p<0.01$) levels than C100+, but N200+ not being significantly different than N100+ on both *Field 1 year* and 2 *years*. Additionally, levels of P were higher in *Field 2 years* (redrilled) than in *Field 1 year* in control plots ($p<0.05$) and in plots receiving Nitram ($p<0.01$) or compost ($p<0.001$), at the second and third samplings. *Field 2 years* also had higher soil K ($p<0.001$) and Mg ($p<0.01$) levels than did *Field 1 year* throughout the samplings with compost application.

Soil dry matter content (DM; results not presented) was significantly higher in plots without weed control (- herb) in the second ($p<0.001$) and in the third ($p<0.05$) samplings in both experiments. Additionally, DM tended to be lower in compost-treated soil throughout the samplings ($p<0.05$), with consistently higher levels of significance in the *Field 2 years* experiment

($p < 0.01$). A significant interaction occurred between type and rate of fertiliser application in *Field 1 year*, where compost-treated plots showed decreasing DM from 100 to 200 kg N.ha⁻¹, whereas Nitram-treated plots showed a slight increase in DM ($p < 0.05$).

Table 6.5 Soil extractable K levels† (mg.kg⁻¹) in the 1995 *Field 1 year* and 2 *years* experiments in Wye (24 Apr is preliminary sampling in *Field 2 years*)

1995	24 Apr	19 Jun (1st smpl)		31 Jul (2nd smpl)		28 Aug (3rd smpl)	
treat	2 years	1 year	2 years	1 year	2 years	1 year	2 years
cont+	204	221	230	110	89	129	139
cont-	177	233	187	117	117	159	126
N100+	197	209	181	131	160	123	133
N100-	170	173	193	103	131	159	152
N200+	163	167	187	124	131	123	139
C100+	246	429	587	181	394	298	478
C100-	280	364	750	146	437	232	363
C200+	362	596	732	245	735	383	714
SED	47.7	81.8	49.4	26.4	65.3	52.0	90.4

† statistical analysis was carried out on logarithmically transformed data due to heterogeneity of variance, but the raw data is presented as results did not differ from the ones obtained before transformation.

Table 6.6 Soil extractable Mg levels (mg.kg⁻¹) in the 1995 *Field 1 year* and 2 *years* experiments in Wye (24 Apr is preliminary sampling in *Field 2 years*)

1995	24 Apr	19 Jun (1st smpl)		31 Jul (2nd smpl)		28 Aug (3rd smpl)	
treat	2 years	1 year	2 years	1 year	2 years	1 year	2 years
cont+	49.3	52.3	52.8	44.2	43.5	41.2	43.3
cont-	49.3	48.3	48.3	43.9	46.8	43.1	41.3
N100+	53.8	49.8	52.7	46.2	52.6	43.0	47.2
N100-	50.2	46.6	51.2	45.5	50.1	40.4	43.7
N200+	48.4	51.8	50.1	48.1	49.1	43.9	43.7
C100+	61.0	53.4	64.2	49.4	64.2	44.6	62.7
C100-	63.7	52.8	67.4	47.8	63.6	42.0	50.4
C200+	66.4	61.8	64.9	56.1	85.6	51.9	67.9
SED	6.59	3.44	7.94	3.23	6.37	1.87	8.17

6.1.3.2 Soil biological assessments

Carbon biomass (BC) was highest in compost-treated plots throughout maize development ($p < 0.05$ and $p < 0.001$, 1st and 3rd samplings respectively), both in field experiments in Wye (*Field 2 years*; Figure 6.4) and in Viterbo (Figure 6.5). In Viterbo, C200+ was also significantly higher than N200+ at the 2nd sampling ($p < 0.05$).

In general, a significant decrease occurred in BC at the second sampling in both the Wye (*Field 2 years*) and Viterbo experiments ($p < 0.05$). At the third sampling, an increase in BC occurred for compost-treated plots ($p < 0.05$), whilst BC continued to decrease in control and Nitram-treated plots, particularly in Wye.

Nitrogen biomass (BN) was also at its lowest values at the second sampling in both the Wye (*Field 2 years*; Figure 6.6) and Viterbo (Figure 6.7) experiments, particularly in compost- and Nitram-treated plots. Figure 6.6 shows that while BN in N200+ remains constant between the last two samplings, in C200+ it tends to increase and in *cont*+ it tends to decrease. Although this is not statistically significant, it is in agreement with previous work (Figure 5.5, Chapter 5 and Viterbo).

In general, no significant differences were found in BN between compost- and Nitram-treated plots. However, both were consistently higher than the control ($p < 0.01$ and $p < 0.05$, respectively) in the experiment in Wye (*Field 2 years*; Figure 6.6). In Viterbo, the only significant difference occurred on the first sampling, control plots having lower BN than Nitram- and compost-treated ones ($p < 0.001$ and $p < 0.05$, respectively), N200+ being also higher than C200+ ($p < 0.05$; Figure 6.7).

The microbial biomass C/N ratio was, in general, similar in experiments both in Wye (*Field 2 years*) and in Viterbo. From the first to the third sampling, it averaged 6, 5, 4 in control plots; 3, 4, 3 in Nitram-; and 6, 5, 6 in compost-treated plots, respectively. With compost application, the C/N ratio was significantly higher than in the control or with Nitram application at the third sampling ($p < 0.05$).

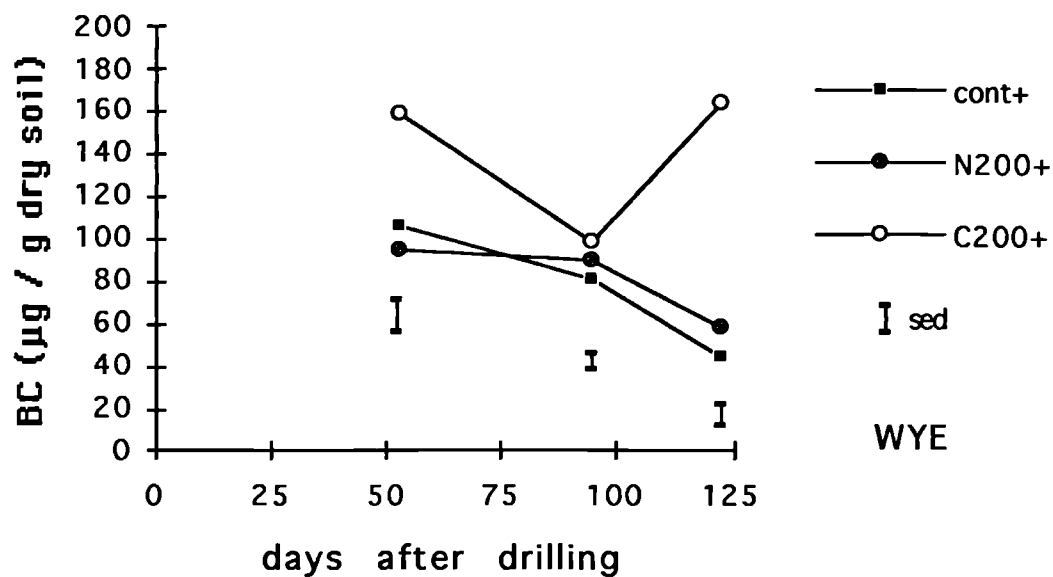


Figure 6.4 Carbon microbial biomass (BC; $\mu\text{g BC.gds}^{-1}$) in the 1995 field experiment in Wye (Field 2 years; gds = g dry soil)

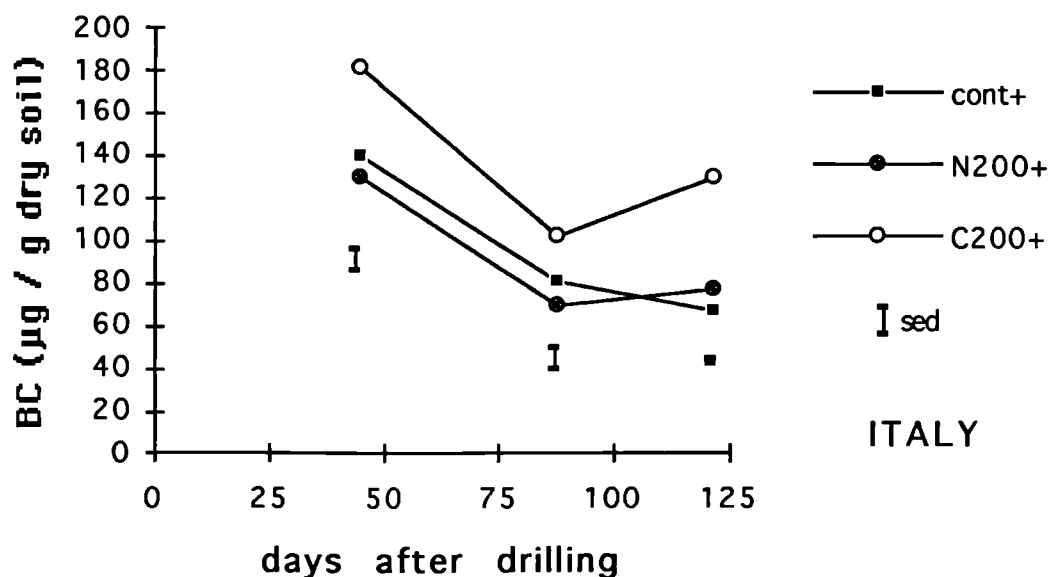


Figure 6.5 Carbon microbial biomass (BC; $\mu\text{g BC.gds}^{-1}$) in the 1995 field experiment in Viterbo, Italy (gds = g dry soil)

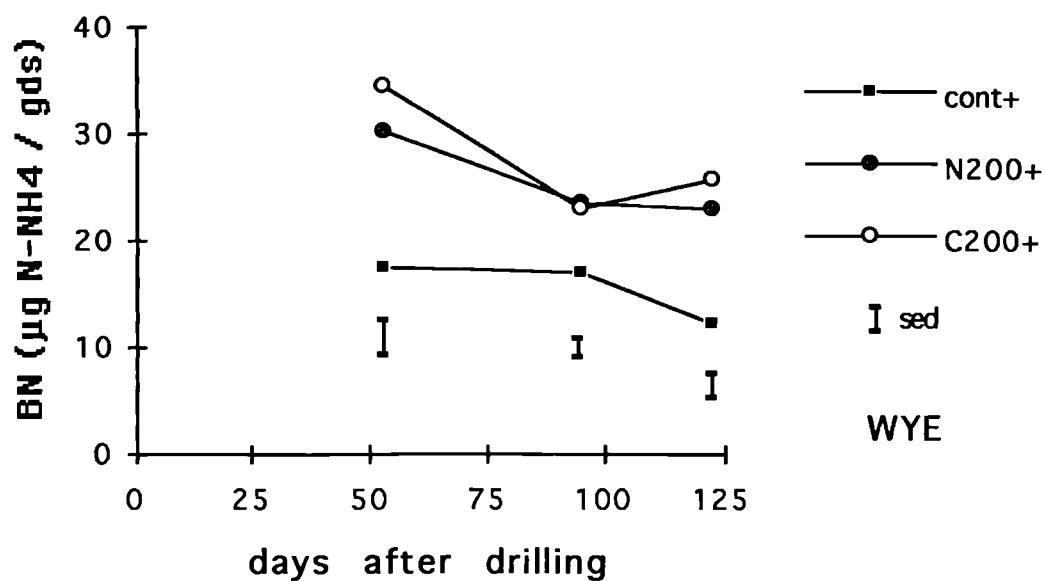


Figure 6.6 Nitrogen microbial biomass (BN; $\mu\text{g NH}_4\text{-N.gds}^{-1}$) in the 1995 field experiment in Wye (*Field 2 years*; gds = g dry soil)

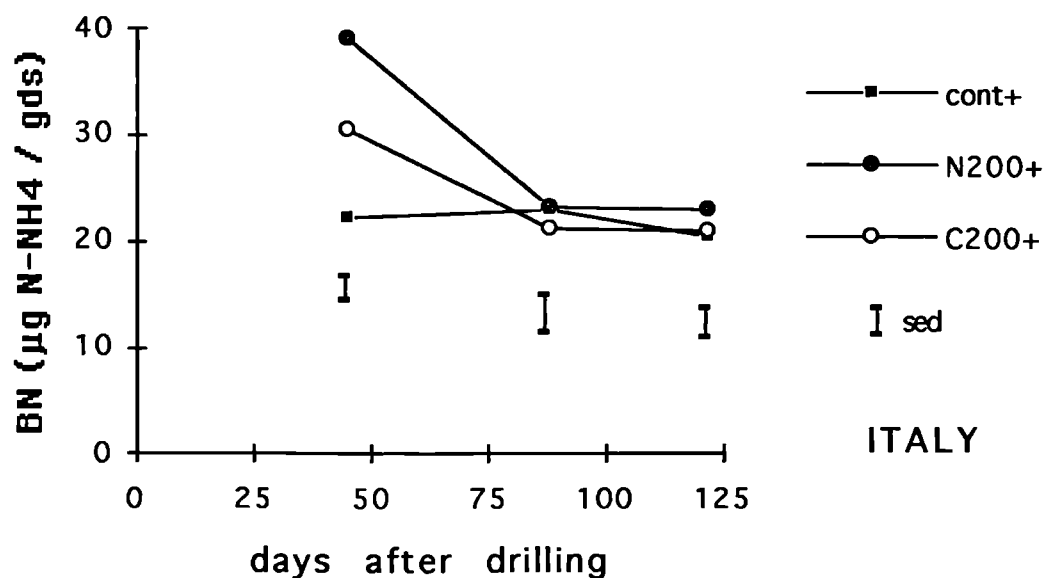


Figure 6.7 Nitrogen microbial biomass (BN; $\mu\text{g NH}_4\text{-N.gds}^{-1}$) in the 1995 field experiment in Viterbo, Italy (gds = g dry soil)

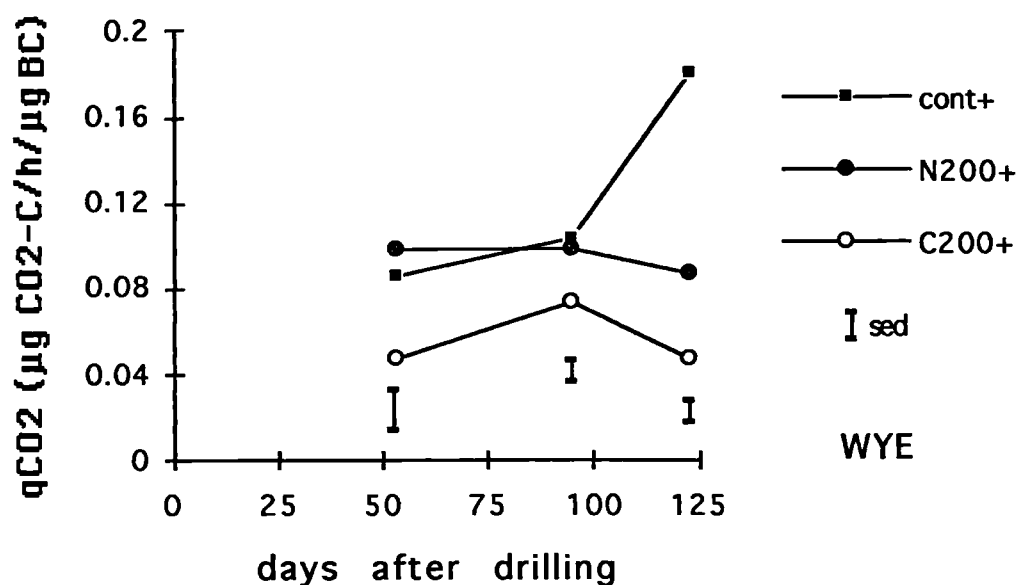


Figure 6.8 Microbial activity (qCO_2 ; $\mu g CO_2-C.h^{-1}.\mu g BC^{-1}$) in the 1995 field experiment in Wye (Field 2 years)

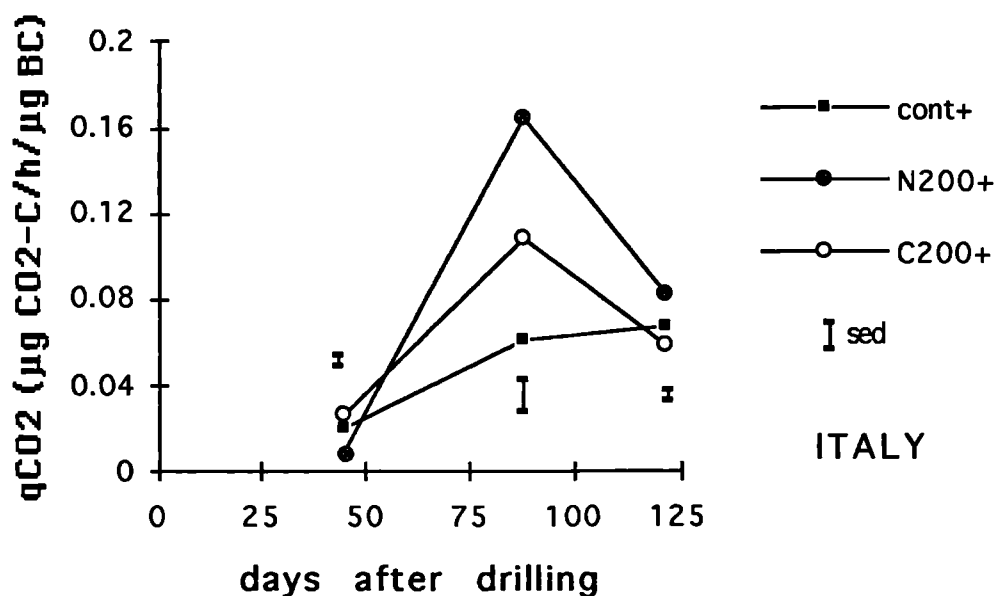


Figure 6.9 Microbial activity (qCO_2 ; $\mu g CO_2-C.h^{-1}.\mu g BC^{-1}$) in the 1995 field experiment in Viterbo, Italy

Microbial activity, expressed as metabolic quotient ($q\text{CO}_2$), tended to be higher in Nitram- than in compost-treated plots in both the Wye (*Field 2 years*; Figure 6.8) and Viterbo experiments (Figure 6.9; $p < 0.05$). A general increase in microbial activity occurred on the second sampling, particularly at the experiment in Viterbo ($p < 0.05$). In plots with Nitram or compost application, the level of activity decreased on the third sampling, whereas it continued to increase in control plots, particularly at the experiment in Wye (*Field 2 years*; $p < 0.001$).

6.1.3.3 Maize Destructive Growth Analyses

Maize fresh biomass results were consistent with those of dry matter production on both *Field 1 year* and *Field 2 years* experiments, and are presented in Appendix 10.

Plots with weed control (+ herb) had significantly higher biomass production in both experiments, particularly at the second and third samplings ($p < 0.001$; Table 6.7; Plate 6.1). Additionally, + herb plots with compost application tended to have higher maize biomass production in *Field 2 years* than in *Field 1 year* ($p < 0.05$).

At 100 kg N.ha^{-1} , Nitram-treated maize tended to have higher biomass than compost-treated maize, although this difference was only significant in the *Field 1 year* experiment, particularly with weed competition (- herb; $p < 0.05$). However, at 200 kg N.ha^{-1} , compost-treated maize tended to have the highest biomass production, particularly on the *Field 2 years* experiment ($p < 0.05$; Plate 6.2).

A significant interaction occurred between type and rate of fertiliser application in *Field 1 year*, as biomass production with increasing N application increased in compost-treated maize but decreased in Nitram-treated maize on the second ($p < 0.05$) and third samplings ($p < 0.001$).

Table 6.7 Maize dry biomass production (g.m⁻²) in the 1995 *Field 1 year* and *2 years* experiments (Wye)

1995	10 Jul (1st DGA)		8 Aug (2nd DGA)		25 Aug (3rd DGA)	
treatment	1 year	2 years	1 year	2 years	1 year	2 years
cont+	110	90	692	670	1070	1120
cont-	80	65	433	243	555	380
N100+	115	85	940	977	1340	1158
N100-	130	75	615	325	740	555
N200+	133	93	885	858	1262	1207
C100+	112	103	750	868	1030	1300
C100-	75	75	337	285	418	343
C200+	97	142	810	905	1375	1405
SED	18.9	18.1	119.1	73.3	125.2	142.4

6.1.3.4 Maize harvest

In general, fresh and dry matter yields and DM content had similar values in both *Field 1 year* and *2 years* experiments in Wye (Tables 6.8 and 6.9, Figure 6.10). However, C100+ showed higher yields in *Field 2 years* (redrilled; $p<0.05$) than in *Field 1 year*.

Table 6.8 Maize fresh biomass yield (t.ha⁻¹) in the 1995 field experiments in Wye (*Field 1 year* and *2 years*) and in Viterbo, Italy

1995	Wye		Viterbo
treatment	1 year	2 years	1 year only
cont+	16.9	18.8	48.3
cont-	9.1	6.1	39.5
N100+	20.2	21.0	58.9
N100-	14.1	8.8	40.6
N200+	20.1	22.5	64.4
C100+	18.7	23.9	56.5
C100-	9.4	6.6	41.6
C200+	21.8	18.7	61.1
SED	2.06	2.50	4.17



Plate 6.1 Maize plots to the left with weed control and maize plots to the right without weed control in the 1995 *Field 2 years* experiment



Plate 6.2 Compost-treated maize plots with 100 (right-hand side) and 200 kg N.ha⁻¹ (left-hand side; taller plants) in the 1995 *Field 2 years* experiment

Maize fresh biomass yields were significantly lower with weed competition (- herb; Table 6.8; $p < 0.001$) in all three experiments. The same occurred with maize dry matter yields in Wye (both experiments; Figure 6.10; $p < 0.001$) and in Viterbo (Figure 6.11; $p < 0.001$). Maize dry matter content at harvest tended to be lower with weed competition (- herb), this being significant in Wye (both *Field 1 year* and *2 years* experiments; Table 6.9; $p < 0.001$).

In Wye, the dry matter content (DM; Table 6.9) at harvest tended to be higher with Nitram than with compost application, with and without weed control, both after one (*Field 1 year*; $p < 0.001$) and after two years of treatment application (*Field 2 years*; $p < 0.01$). In Viterbo, DM content at harvest did not differ between Nitram- and compost-treated maize, but both were significantly higher than in control, particularly without weed competition (+ herb; $p < 0.05$).

Table 6.9 Maize dry matter content (DM %) in the 1995 field experiments in Wye (*Field 1 year* and *2 years*) and in Viterbo, Italy

1995 treatment	Wye		Viterbo
	<i>1 year</i>	<i>2 years</i>	<i>1 year only</i>
<i>cont+</i>	33.7	33.0	26.9
<i>cont-</i>	32.2	30.4	27.9
<i>N100+</i>	36.3	34.6	29.8
<i>N100-</i>	35.8	31.7	27.1
<i>N200+</i>	36.0	32.9	30.4
<i>C100+</i>	32.8	32.1	30.1
<i>C100-</i>	30.7	29.6	29.4
<i>C200+</i>	32.9	32.2	29.9
SED	0.85	0.77	1.59

No significant differences were found in either fresh or dry matter yields between plots receiving compost and Nitram on all three 1995 field experiments. However, on the *Field 1 year* experiment in Wye, Nitram-treated maize had higher fresh and dry matter yields than compost in the presence of weeds (- herb; $p < 0.05$ and $p < 0.01$, respectively; Table 6.8 and Figure 6.10). The opposite occurred in Viterbo, with *C100-* having higher DM yield than *N100-*, although this difference was not significant (Figure 6.11).

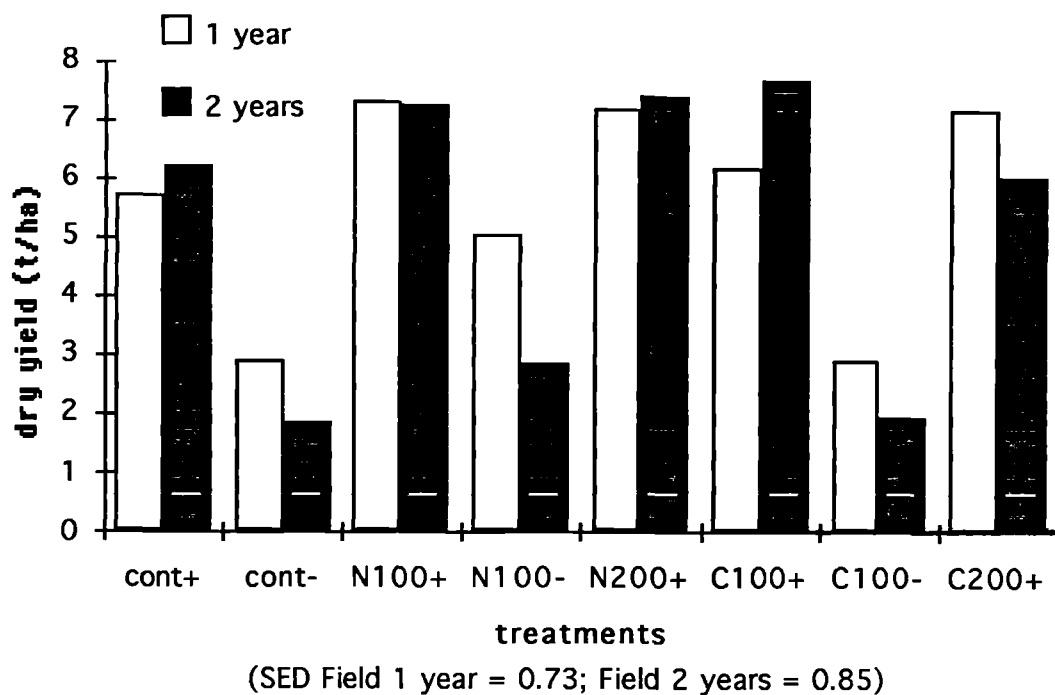


Figure 6.10 Maize dry matter yield ($\text{t}\cdot\text{ha}^{-1}$) in the 1995 *Field 1 year* and *2 years* experiments (Wye)

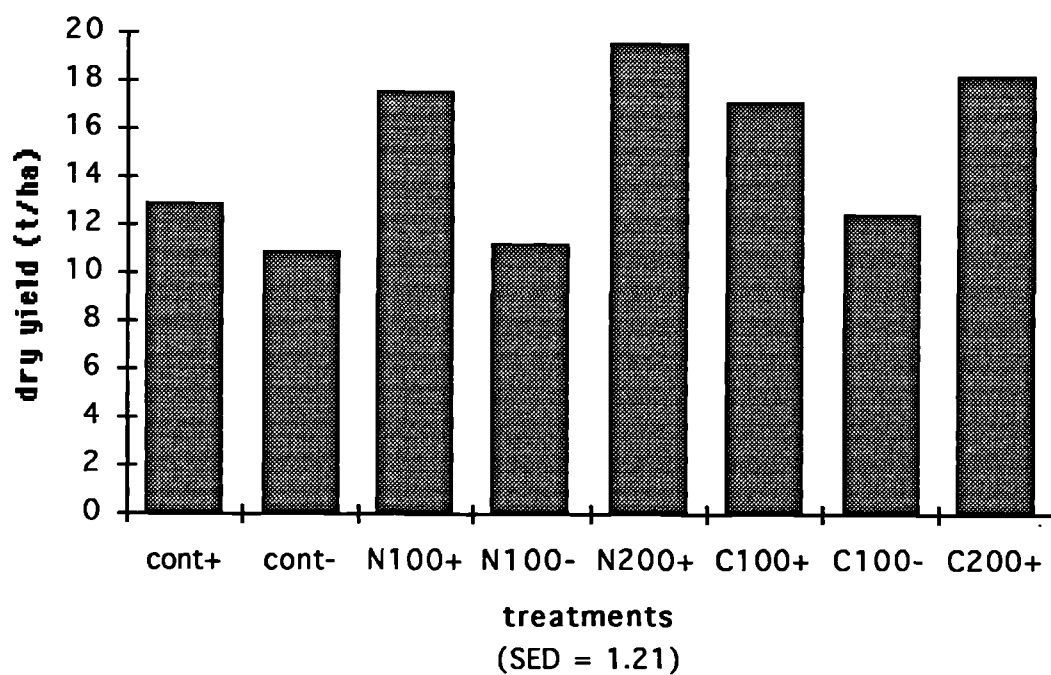


Figure 6.11 Maize dry matter yield ($\text{t}\cdot\text{ha}^{-1}$) in the 1995 field experiment in Viterbo, Italy

In general, maize fresh and dry matter yields did not vary with increasing rates of N fertilisation in all three experiments (Table 6.8, Figure 6.10 and Figure 6.11). However, although the separate comparisons are not statistically significant, mean yields from plots with the higher rates of compost (in Viterbo and Wye) or Nitram (in Viterbo only) had consistently higher fresh and dry matter yields. In the *Field 2 years* experiment in Wye, C200+ maize yielded less than C100+ ($p<0.05$).

The feeding quality of maize forage at harvest in both 1995 field experiments in Wye was determined by two parameters, estimated in Table 6.10: cob expressed as percentage of total dry matter production (cob as % DM) and forage digestibility, determined by the Neutral detergent/Cellulase Digestibility method (% NCD; MAFF 1989). Both were significantly lower in the presence of weeds (- herb; $p<0.001$). Nitram-treated maize had higher cob as % DM than compost ones at 100 kg N.ha⁻¹, with (+ herb; *Field 1 year*; $p<0.001$) and without (- herb; *Field 1 and 2 years*; $p<0.01$) weed control.

Table 6.10 Cob expressed as % of dry matter and maize digestibility (NCD %) in the 1995 *Field 1 year* and *2 years* experiments (Wye)

1995 treatment	cob as % DM		digestibility (NCD %)	
	<i>1 year</i>	<i>2 years</i>	<i>1 year</i>	<i>2 years</i>
cont+	49.4	49.2	76.3	77.4
cont-	39.2	30.2	74.2	71.0
N100+	53.3	48.3	78.3	78.7
N100-	44.6	28.8	76.5	73.2
N200+	53.8	51.7	78.5	77.1
C100+	34.3	48.3	77.1	78.1
C100-	30.2	12.9	74.8	71.3
C200+	48.6	49.0	76.4	78.5
SED	3.88	4.75	0.64	1.50

No further significant differences were found in the *Field 2 years* (redrilled), but in *Field 1 year* a significant interaction occurred between type and rate of fertiliser application ($p<0.001$). Cob as % DM increased with increasing rates of compost application, but remained constant at both rates of Nitram application. Additionally, digestibility was higher in Nitram- than in compost-treated maize in the presence of weeds (N100- and C100-; $p<0.05$)

and at the higher rate of N application (N200+ and C200+; $p < 0.01$). However, maize in compost-treated plots had higher percentage of cob in its dry matter ($p < 0.05$) and higher digestibility ($p < 0.01$) in *Field 2 years* than did in *Field 1 year*.

6.1.3.5 Maize nutrient uptake

Maize uptakes of N, P, K, Ca and Mg was higher in plots with weed control (+ herb; $p < 0.001$). Nitrogen uptake was higher in Nitram- than in compost-treated maize at 100 kg N.ha⁻¹ in *Field 1 year*, and at 200 kg N.ha⁻¹ in *Field 2 years* (Figure 6.12; $p < 0.05$). However, N uptake by compost-treated maize was higher in *Field 2 years* than in *Field 1 year*, particularly with C100+ ($p < 0.05$).

Uptake of K tended to be highest in compost-treated maize on both experiments in Wye, the difference being significant in *Field 2 years* at 100 kg N.ha⁻¹ (Figure 6.13; $p < 0.05$).

Table 6.11 Maize total P, Ca and Mg uptake (kg.ha⁻¹) in the 1995 *Field 1 year* and *2 years* experiments (Wye)

1995 treatment	Phosphorus		Calcium		Magnesium	
	<i>1 year</i>	<i>2 years</i>	<i>1 year</i>	<i>2 years</i>	<i>1 year</i>	<i>2 years</i>
cont+	7.4	7.3	17.7	17.8	5.1	5.6
cont-	3.5	1.9	10.7	6.4	2.7	1.9
N100+	8.3	8.3	19.1	16.4	5.7	6.7
N100-	5.4	3.0	15.5	9.2	4.5	3.1
N200+	7.7	8.6	19.0	18.4	6.2	7.1
C100+	7.2	9.3	16.8	14.6	5.1	6.4
C100-	3.3	2.0	9.7	6.6	2.6	1.9
C200+	7.9	6.9	19.2	12.9	6.0	5.1
SED	0.79	1.09	1.78	2.03	0.54	0.76

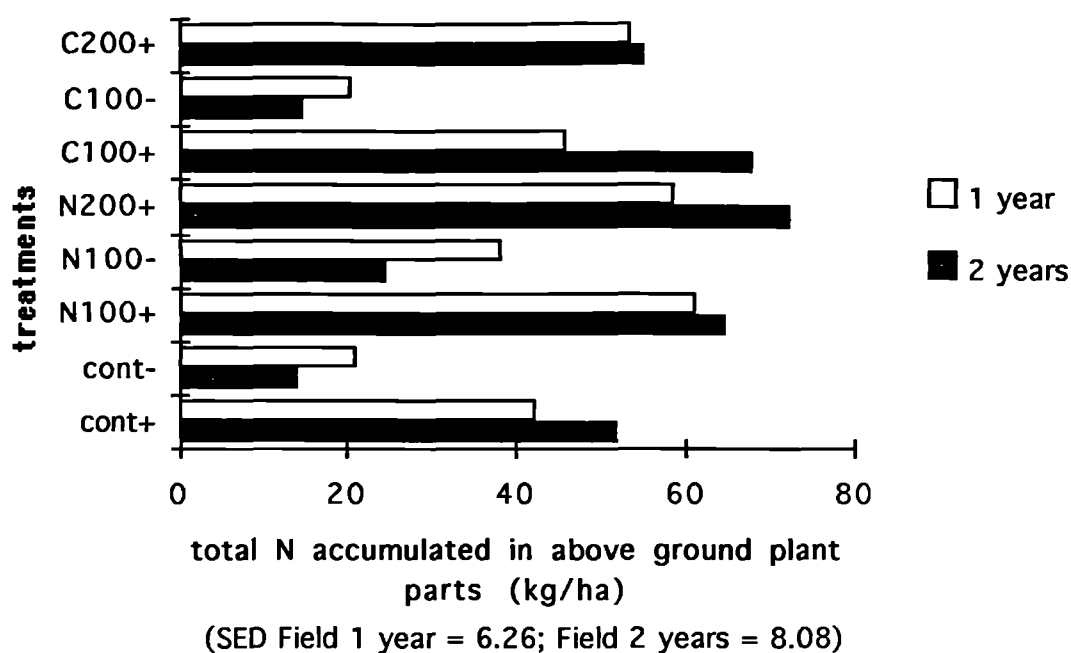


Figure 6.12 Maize total nitrogen uptake ($\text{kg}\cdot\text{ha}^{-1}$) in the 1995 *Field 1 year* and *2 years* experiments (Wye)

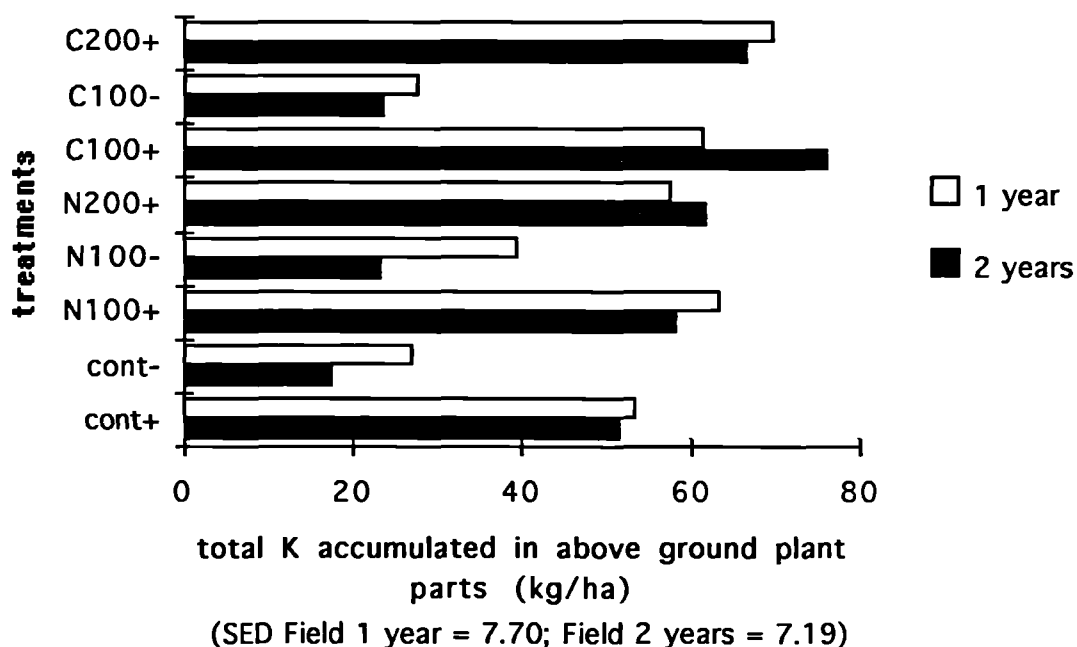


Figure 6.13 Maize total potassium uptake ($\text{kg}\cdot\text{ha}^{-1}$) in the 1995 *Field 1 year* and *2 years* experiments (Wye)

In *Field 1 year*, N100- had higher maize P ($p<0.05$), Ca and Mg ($p<0.01$) uptake than C100-, but that did not occur in *Field 2 years* (Table 6.11). Nutrient uptake tended to be lower in C200+ than C100+ in *Field 2 years*, this being significant for P uptake ($p<0.05$). Additionally, C200+ had lower uptake of Ca and Mg than N200+ ($p<0.05$). Both P and K uptakes by maize were higher in *Field 2 years* than in *Field 1 year* at C100+ plots ($p<0.05$).

6.1.3.6 Weed analyses

Table 6.12 Weed dry biomass production (g.m^{-2}) in plots without weed control (- herb) in the 1995 *Field 1 year* and *2 years* experiments (Wye)

1995	10 Jul (1st DGA)		8 Aug (2nd DGA)		25 Aug (3rd DGA)	
treatment	1 year	2 years	1 year	2 years	1 year	2 years
cont-	44.7	66.6	119.4	178.3	75.8	152.0
N100-	54.5	71.5	91.3	216.5	70.1	192.6
C100-	63.5	97.7	82.9	212.1	54.6	223.5
SED	23.36	17.68	32.96	66.88	12.16	49.89

No significant differences were found in weed dry biomass production between treatments on both experiments in Wye, but *Field 1 year* had generally lower weed infestation than *Field 2 years* (Table 6.12; $p<0.05$).

Table 6.13 Weed total N, P, K, Ca and Mg uptake (kg.ha^{-1}) in plots without weed control (- herb) in the 1995 *Field 1 year* and *2 years* experiments (Wye)

treatment	N uptake	P uptake	K uptake	Ca uptake	Mg uptake
<i>Field 1 year experiment</i>					
cont-	10.9	1.1	16.2	12.3	0.8
N100-	11.4	1.2	17.3	12.5	1.0
C100-	9.2	1.0	14.6	9.5	0.8
SED 1 year	1.49	0.15	1.98	2.09	0.21
<i>Field 2 years experiment</i>					
cont-	20.3	2.4	29.8	21.7	2.6
N100-	27.4	3.0	35.6	25.5	2.9
C100-	30.5	4.4	50.1	28.9	3.3
SED 2 years	7.40	0.89	9.55	7.39	0.78

Weed species which occurred in the field were not associated with additives, and are presented in Appendix 7. No significant differences between treatments were found in nutrient uptake by weeds on both experiments in Wye (Table 6.13), although concentrations of P and K on the weed tissues were higher in compost-treated plots, particularly in *Field 2 years* ($p < 0.01$; data not presented). Although experiments were analysed separately, it was found that uptake of nutrients by weeds was higher in *Field 2 years* than in *Field 1 year* experiment ($p < 0.05$ for P, $p < 0.01$ for N, K, Ca and Mg).

6.1.4 Discussion

Soil chemical fertility was enhanced by compost application, indicated by the higher total N, P, K and Mg levels on compost-treated soil in the field experiments in Wye. A residual effect from compost application on the previous growing season was observed in *Field 2 years*, which was a redrill of the 1994 Field A experiment (Chapter 5). Levels of P, K and Mg were highest on compost-treated plots in the preliminary soil sampling, carried out before any fertiliser was applied in 1995. Additionally, although experiments were analysed separately, a cumulative effect of compost on soil nutrients was suggested by the higher levels of P, K and Mg levels observed in *Field 2 years* than in *Field 1 year*. The differences between results of *Field 1 year* and *2 years* experiments could be due to the fact that they were in different areas of land, as well as receiving either one or two applications of compost, respectively. However, comparisons of control plots in the two experiments shows generally great similarity, thus suggesting that differences in nutrient levels or yields are due to the cumulative effect of compost. Moreover, these results are similar to those reported by Brinton (1985), Ott (1990) and Sharpley and Smith (1995).

Potassium levels in soil were particularly high with compost application, as dairy manure used for compost production is rich in this nutrient (Pain 1978; Kiehl 1985). Higher soil K levels resulted in higher K uptake by the maize and weed plants, especially after two years of compost application. This 'luxury' consumption of K was probably the cause for the lower Ca and Mg uptake of compost-treated maize. As plants absorb K^+ ions (mono-valency) in preference to Ca^{++} and Mg^{++} ions (di-valency), and as the sum of K, Ca and Mg individual percentages in plant is usually held constant, a higher concentration of K in soil invariably leads to lower Ca and Mg levels in the plant tissue (Tisdale and Nelson 1975; Pain 1978; Marschner 1986).

Despite being originally high in the Wye soil, its organic matter (OM) increased still further in compost-treated plots, showing higher levels after even only one year of application (*Field 1 year*). Accumulation of soil OM was suggested by a larger difference between treatments after two consecutive compost application (*Field 2 years*). However, effects of compost application in soil OM would probably be more evident in conditions of lower original soil organic matter, as in the experiment in Viterbo.

A lower soil moisture content due to weed competition for water was indicated by the higher soil dry matter content (DM) in plots with the presence of weeds (- herb). Water availability to plants was higher in compost- than in Nitram-treated soil, increasing with increased rates of compost application, but not with Nitram. A cumulative effect of compost was also suggested by the larger difference in soil DM between compost and Nitram plots in *Field 2 years* than in *Field 1 year*, indicating a higher soil water content with two years of compost application. This is probably related to the higher soil organic matter content of compost plots, resulting in increased soil water holding capacity (Dalzell *et al* 1987; Tester 1990).

The alkaline pH of the soil in Wye and its aerobic conditions were likely to be the cause for the very low levels of soil ammonium, as nitrification processes are faster at high pH conditions (Rochester *et al* 1992). Moreover, Olsen *et al* (1970) reported on very small amounts of exchangeable $\text{NH}_4\text{-N}$ being found under aerobic conditions, where $\text{NO}_3\text{-N}$ was predominant.

Nitrate levels were highest in Nitram-treated soil, showing a positive relation with Nitram rates of application, and significantly higher levels after two consecutive years (*Field 2 years*) of application. In contrast, nitrate levels remained low at both rates of compost application throughout the growing season in both experiments. N uptake of maize is minimal during its initial stages of development, increasing slowly to reach a maximum between flowering and early grain formation, and decreasing thereafter, as N is translocated from vegetative parts to the ear (Pain 1978). Hence, excessive nitrate in soil before and after the period of higher N uptake by maize is likely to leach (Magdoff 1991; Maynard 1993). Therefore, compost had a lower potential for nitrate accumulation, leaching and pollution than Nitram, particularly after consecutive applications.

The lower nitrate levels in plots without weed control indicated that weeds were competing with maize for the readily available nitrogen. This competition resulted in lower maize biomass production and nutrient uptake in the presence of weeds in general. Maize benefited then from the extra available nitrate in Nitram-treated plots in Wye, which had higher biomass production and nitrogen uptake than compost ones in the presence of weeds, with one year of fertiliser application. However, the absence of these differences in *Field 2 years* indicates that compost would tend to supply higher levels of readily available N with consecutive applications, as the soil ecosystem adjusted to a new equilibrium with organic inputs (Doran *et al* 1987). This tendency was further indicated by the increasing nitrate levels in compost-treated plots in *Field 2 years* (redrilled) compared to *Field 1 year* experiment. Moreover, microbial-mediated processes such as mineralisation of organic matter were expected to be faster in warmer conditions (Duxbury *et al* 1989; Dick and McCoy 1993). The higher maize biomass production in compost- than in Nitram-treated maize with weed competition in Viterbo, as opposed to in Wye, was probably due to better conditions of compost N mineralisation in the Mediterranean than the temperate climate.

Compost application enhanced soil biological fertility, as reported in the literature (Anderson and Domsch 1989; Perucci 1990; Wardle 1992). Compost-treated plots had the highest levels of microbial biomass carbon (BC) both in Wye and in Viterbo. Microbial biomass nitrogen (BN) was also higher with compost application in Wye, although not significantly different from that with Nitram, but both fertilisers had higher BN than did the control. In Viterbo, BN benefited at first from the extra nitrogen added with Nitram and compost, but afterwards BN decreased to levels as low as in the control. This was a result of the lower available levels of N during crop development, but also indicated the higher turnover of N biomass in faster mineralisation conditions (Ross *et al* 1995), when compared to BN levels in Wye.

Microbial activity is associated with nitrogen mineralisation processes. However, increases in microbial activity can also denote conditions of disturbance to the microorganisms, such as lower nutrient availability (Wardle *et al* 1993). Microbial activity, expressed as metabolic quotient, was higher in Nitram- than in compost-treated plots, probably due to the lower carbon availability in the former, as C is usually limited in soil (Fraser *et al* 1988; Anderson and Domsch 1989). Additionally, microbial activity was

generally higher in Viterbo than in Wye, reflecting the lower soil organic matter content in the former (thus lower nutrient availability for microorganisms), and the accelerated microbial biomass turnover in warmer conditions (Insam *et al* 1991; Ross *et al* 1995). Although lower microbial activity results in lower mineralisation rates, the levels of N made available in compost-treated soil were apparently adequate for maize development in Wye, as indicated by the general absence of significant differences in maize dry matter yields between treatments.

A general decrease in microbial biomass (BC and BN) with an increase in microbial activity coincided with maize flowering, indicating that more N was being mineralised and made available to the crop at the period of its higher N demand. It also indicated the higher competition for nutrients between maize and microorganisms at that stage. Ghoshal and Singh (1995) reported similar results. As nutrient uptake by maize decreased towards the end of its development, microbial biomass increased and metabolic quotient decreased, particularly in compost-treated soil, with nutrients again available for microorganisms; and particularly in Wye, with higher soil OM and slower biomass turnover than in Viterbo. The increase in microbial biomass in compost-treated plots when crop competition ceased is in agreement with previous works (Chapter 5, Viterbo; Fauci and Dick 1994b). However, microbial biomass remained low and activity levels increased in control plots both in Wye and in Viterbo at the end of maize development. That was probably because the nutrient availability for microorganisms had been greatly reduced by competition during maize flowering, and nutrient levels remained low as no fertiliser had been added.

The decrease in the microbial C/N ratio in control plots from the start to the end of the crop development also indicated the gradually lower C and N availability. Likewise, the increase in microbial C/N ratio at the end of the crop development in compost-treated plots reflected an increase in C supply after the critical period of maize competition for nutrients was finished. In general, the C/N ratio of microorganisms was higher with compost than with Nitram application, showing a direct relationship between the C/N ratio of organic inputs and the C/N ratio of microbial biomass. The microbial community in soil with organic inputs has a higher percentage of fungi, which are responsible for degradation of the more complex molecules, and which have a higher C/N ratio (above 6) than bacteria (below 6; Wardle 1992; N. Gunapala and K. M. Scow, pers. comm.). Thus, microbial biomass in

compost-treated soils will tend to have a higher C/N ratio than those in Nitram-treated soils.

Without weed competition, no significant differences in final biomass production were found between Nitram and compost-treated maize, both showing higher yields than the control. Results indicate that levels of mineralised N from compost in soil, despite being lower than the readily available N supply of Nitram, were adequate for maize development. During the growing season, maize tended to have higher biomass production with compost than with Nitram application, particularly at the higher rate of application and after two years (*Field 2 years*). N uptake by compost-treated maize was higher in *Field 2 years* than in *Field 1 year*, particularly with C100+. Thus, although maize N uptake was lower with compost than with Nitram application in *Field 1 year*, in *Field 2 years* they showed similar levels at 100 kg N.ha⁻¹. Results are in agreement with those of nitrate levels, and further indicate a tendency of increased nitrogen supply with consecutive applications of compost, which can be related to the increased size of soil microbial biomass, and to its turnover once the soil ecosystem is more adjusted to organic inputs (Jenkinson and Ladd 1981; Doran *et al* 1987; Fauci and Dick 1994a). Increased N supply with consecutive compost application could result in higher maize biomass production in the longer term (Fraser *et al* 1988; Suzuki *et al* 1990).

The attack on maize by hares at the end of August caused a severe reduction (approximately 50%) in yields of two out of the four plots treated with the higher rate of compost (C200+) in the redrilled experiment (*Field 2 years*). Doubtless, that was the reason for the lower average final maize yields and nutrient uptake with compost after two years of application at 200 kg N.ha⁻¹. These results were opposite to those expected, as maize fresh and dry matter yields tended to increase from the lower to the higher rate of compost application both in the *Field 1 year* in Wye and in the Italian experiment. Moreover, maize with compost application at 100 kg N.ha⁻¹ had higher biomass production in *Field 2 years* than in *Field 1 year*, further indicating that the potential of compost to enhance maize production increases with consecutive applications.

A higher weed infestation occurred in the eastern area of the experiments (Figure 6.1), which coincided with *Field 2 years*. For this reason, it had higher weed biomass production and weed nutrient uptake than *Field 1 year*, these

results not being related to any particular fertiliser. This was indicated by the higher weed dry matter production and nutrient uptake in *Field 2 years* than in *Field 1 year* even in control plots.

The feeding quality of forage was lower in plots without weed control, as the results of lower cob expressed as percentage of dry matter and lower digestibility (percentage of NCD) indicated. As the cob is the more digestible part of the maize plant, a lower percentage of cob results in a lower feeding quality of the forage (Wilkinson 1978). Cob formation was reduced in plots without herbicide application due to competition of weeds with maize plants for the available nutrients. Additionally, as weeds were present in the maize rows, a part of them was probably harvested with the maize, explaining the fact that the resulting material had a lower digestibility than did maize with no weed infestation. Nearly two-thirds of the total N accumulated by maize at its maturity is concentrated in the cob (Pain 1978; Fageria *et al* 1991). Moreover, a higher N supply reduces the lignin and the fibre content of maize forage, thus increasing its digestibility (Pain 1978). These were probably the reasons for Nitram-treated maize showing a higher percentage of cob in its dry matter and a higher digestibility than compost-ones, but only at the lower rate and in *Field 1 year*. With consecutive applications (*Field 2 years*), these differences no longer existed, as both the percentage of cob in maize dry matter and the maize digestibility increased in compost-treated plots, probably as a result of the increased maize yields and N uptake.

Maize dry matter content tended to be lower with compost than with Nitram application in Wye, but not in Viterbo. That could be related to the higher soil water availability in compost-treated plots in Wye (Dalzell *et al* 1987), where climatically drier conditions were experienced than in Viterbo. Additionally, the high levels of K in the tissue of compost-treated maize could contribute to its lower dry matter content, as K regulates the use of water by the plant, increasing its uptake and reducing its loss (Marschner 1986). The lack of differences between treatments in Viterbo could be associated with a higher supply of N from compost, as its higher temperatures resulted in faster mineralisation conditions than in Wye, allowing for increased accumulation of maize dry matter with compost application.

6.1.5 Conclusions

Both chemical (levels of N, P, K, Mg) and biological (size of microbial biomass) fertility of the soil are enhanced by composted dairy manure, the effect apparently being higher with consecutive applications.

Soil treated with compost has higher organic matter content and water holding capacity, apparently even more so with consecutive applications.

Compost has a lower potential for nitrate leaching and pollution even after continuous application, as nitrate levels in soil are lower with the use of compost than with mineral fertiliser, remaining lower with consecutive compost addition.

The supply of available N by compost is larger after successive applications, probably due to a larger microbial biomass and to increased mineralisation.

Microbial-mediated processes are accelerated in a warmer climate, with a higher turnover of microbial biomass.

Also, in conditions of lower soil organic matter content, microorganisms have higher metabolic quotient (less efficient respiration processes), due to more competition for nutrients. Thus, N mineralisation rates can also be higher.

When maize nutrient uptake is highest, microorganisms have reduced biomass and increased activity, due to competition for nutrients. However, microbial biomass is greater with compost application, and tends to increase again when competition ceases, indicating that addition of compost can sustain soil biological fertility.

Weed competition for resources, such as nutrients and water, severely reduces maize development and yields.

The feeding quality of forage maize is greatly reduced in the presence of weeds.

Compost can supply adequate levels of nutrients to ensure maize yields similar to those obtained with commercial amounts of chemical fertilisers.

There is a tendency for nutrient supply to increase with repeated compost application, due to the cumulative effects of compost on soil organic matter and microbial biomass. A higher nutrient supply potentially results in higher crop biomass production and in higher feeding quality of the forage. However, longer term experiments are necessary to examine whether this potential is realised.

Chapter 7. The Glasshouse Experiments

7.1 The 1993 Glasshouse Experiment - Effects of different rates of dairy manure compost on maize (*Zea mays* L.) nitrogen nutrition

7.1.1 Introduction

Crop response to organic fertilisers varies greatly depending on the composition of the fertiliser and the quantities applied. Conflicting information is available in the literature regarding the optimal rates to meet nutrient requirements and to produce satisfactory crop yields (Mathers and Goss 1979; Kiehl 1985; Sahs and Lesoing 1985; Serna and Pomares 1992). Therefore, prior to using dairy manure compost as a fertiliser for forage maize in field experiments (Chapters 4-6), it was important to determine the application rates most likely to provide an adequate supply of nutrients (in particular nitrogen). A plant growth indicator test was used to study the potential nitrogen supply from compost to plants, being a biological method commonly found in the literature (Navarro *et al* 1992).

7.1.1.1 Objectives

This preliminary glasshouse experiment was set up to test different amounts of composted dairy manure as a nitrogen supplier for maize under controlled conditions. Two rates of compost application (low and high) were to be selected to be used in the 1993 field experiment (Chapter 4). Compost was compared with chemical N fertiliser to consider its value as a fertiliser.

7.1.2 Material and methods

An experiment was established with ten treatments, consisting of six rates of dairy manure compost, three rates of inorganic N fertiliser (Nitram) application and one untreated control. The rates of compost were equivalent to 25, 50, 100, 150, 200 and 250 t fresh weight.ha⁻¹. Nitram (34.5% N) was applied at rates equivalent to the available N (NO₃-N + NH₄-N) content of 50, 150 and 250 t of compost.ha⁻¹, respectively (Table 7.1). A randomised complete block design was used with ten replications (total of 100 pots).

Dairy manure and peat compost (used as substrate) were sampled prior to the start of the experiment and analysed for their nutrient composition (Appendix 3). Dairy manure compost had 0.05% of available N ($\text{NO}_3\text{-N} + \text{NH}_4\text{-N}$). The available N content of peat compost was considered negligible.

Table 7.1 Treatments used in 1993 glasshouse experiment

Treatment	Description	Available N ($\text{kg}\cdot\text{ha}^{-1}$)
1. <i>cont</i>	untreated control	0.00
2. <i>N22</i>	Nitram equiv. to C22 (50 t compost. ha^{-1})	22.50
3. <i>N67</i>	Nitram equiv. to C67 (150 t compost. ha^{-1})	67.50
4. <i>N112</i>	Nitram equiv. to C112 (250 t compost. ha^{-1})	112.50
5. <i>C11</i>	Compost 25 t fresh weight. ha^{-1}	11.25
6. <i>C22</i>	Compost 50 t fresh weight. ha^{-1}	22.50
7. <i>C45</i>	Compost 100 t fresh weight. ha^{-1}	45.00
8. <i>C67</i>	Compost 150 t fresh weight. ha^{-1}	67.50
9. <i>C90</i>	Compost 200 t fresh weight. ha^{-1}	90.00
10. <i>C112</i>	Compost 250 t fresh weight. ha^{-1}	112.50

The experiment was established and assessed as described in Section 3.4 (Chapter 3), starting on 26 February 1993. Maize emergence occurred one week later. Plant height was measured once a week after emergence. Shoot biomass production (fresh and dry matter), maize leaf area and nutrient uptake (N, P, K, Ca and Mg) were assessed twice, as follows: five blocks (50 pots) were randomly sampled at day 45 of the start of the experiment, maize at Growth Stage (GS) 3.25 - 8/9 leaves, and the remaining five blocks were sampled at day 60 (Plate 7.1), maize at GS 4.25 - 12/13 leaves (Groot *et al* 1986, Appendix 1). Maize nutrient uptake, i.e. the amount of nutrient accumulated in the above ground plant parts was calculated: nutrient uptake ($\text{kg}\cdot\text{ha}^{-1}$) = nutrient concentration ($\text{kg nutrient}\cdot\text{kg DM}^{-1}$) * dry matter production ($\text{kg DM}\cdot\text{ha}^{-1}$).

Statistical analysis of data (analysis of variance followed by orthogonal contrasts) was carried out using GENSTAT (Genstat 5 Committee 1987) and Macintosh SuperANOVA GLM program (Abacus Concepts 1989). In a few of the datasets, treatments had heterogeneous variances and, for these, analysis of variance was also carried out on logarithmically transformed

data (Finney 1989). However, as the conclusions were similar to those obtained before data transformation, all results are based on raw data.

7.1.3 Results

Plant height, leaf area and shoot fresh weight results were consistent with those for shoot dry matter production and are not presented. Maize dry matter production (sum of the three plants in g.pot⁻¹) at 45 and at 60 days from the start of the experiment are presented in Figures 7.1 and 7.2, respectively.

Compost treatments had clearly higher dry matter yields ($p < 0.001$) than Nitram and the control after both 45 and 60 days of the experiment. Maize biomass production was not significantly altered with increasing rates of Nitram application and did not differ from the untreated control, at both stages of maize development. Compost-treated maize also showed no significant difference in dry matter production between all rates of application, at 45 days of the experiment. However, a quadratic trend ($p < 0.01$) in the response of dry weight to increasing compost was found at the end of the experiment. Dry biomass production reached a peak at C67 (150 t of compost.ha⁻¹), which was not significantly different from the higher application rates.

Maize nitrogen uptake (kg.ha⁻¹) at 45 and at 60 days of the experiment are shown in Figures 7.3 and 7.4, respectively. At 45 days, maize N uptake was significantly higher ($p < 0.001$) in compost treatments compared to Nitram at the higher rates of application (67.5 and 112.5 kg.ha⁻¹), but no significant difference was found between compost and Nitram at the lower rate of application (N22 and C22).

At the end of the experiment (60 days), no significant difference was found in maize N uptake between Nitram and compost treatments at equivalent rates of application. However, maize N uptake increased linearly with increasing rates of compost ($p < 0.01$), but no significant difference was found within Nitram treatments.

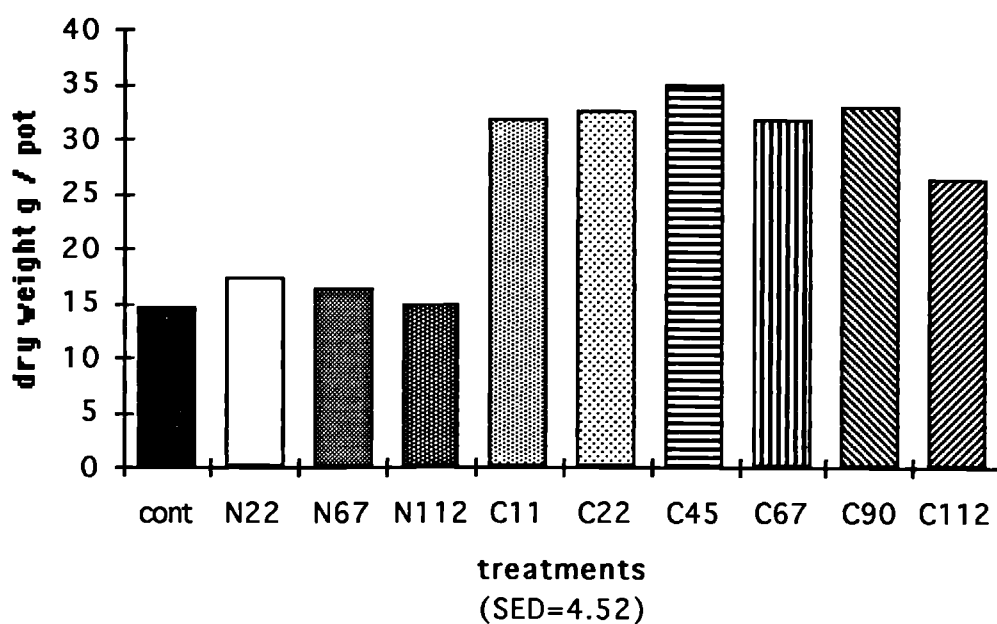


Figure 7.1 Maize dry matter production (g.pot^{-1}) at 45 days from the experiment start (1993 glasshouse experiment)

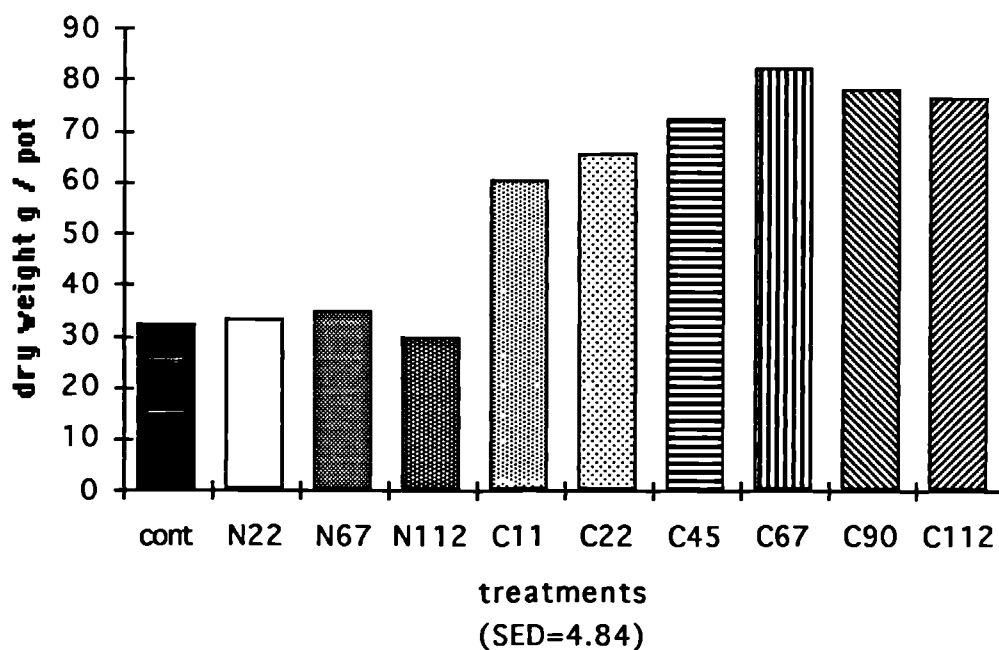


Figure 7.2 Maize dry matter production (g.pot^{-1}) at 60 days from the experiment start (1993 glasshouse experiment)

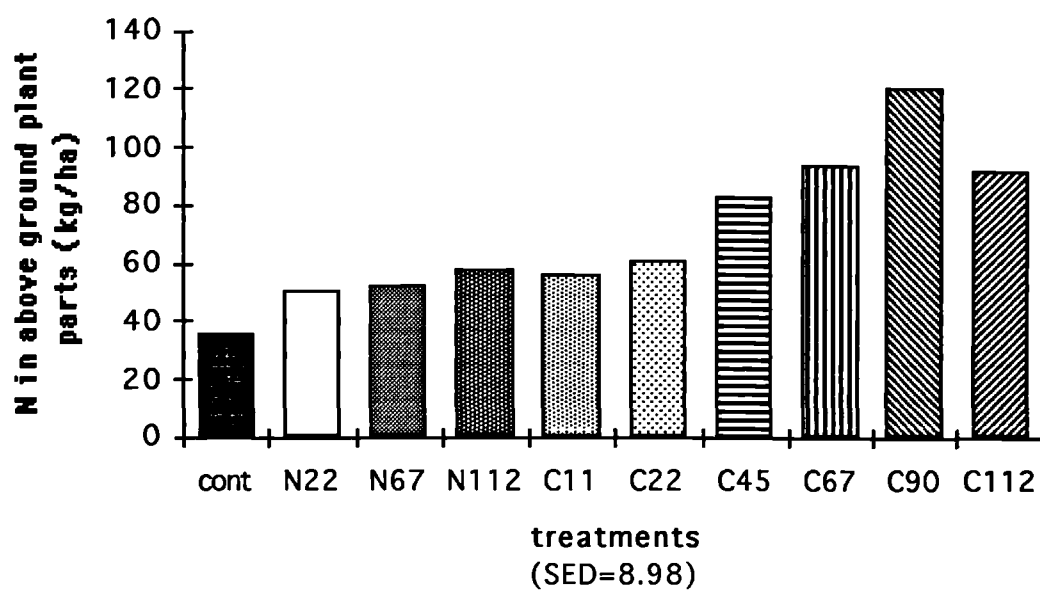


Figure 7.3 Nitrogen uptake by maize ($\text{kg}\cdot\text{ha}^{-1}$) at 45 days in the 1993 glasshouse experiment

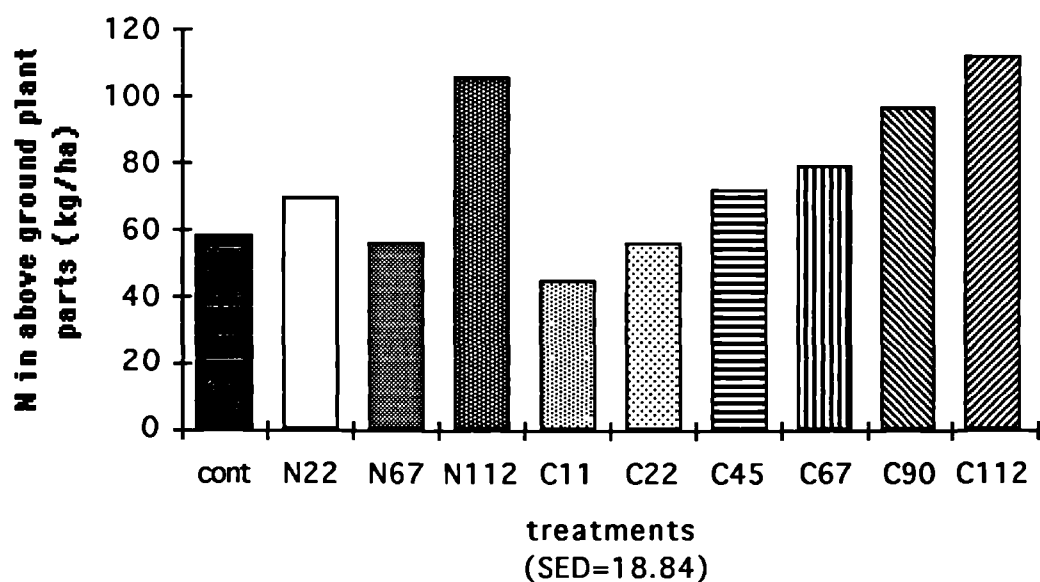


Figure 7.4 Nitrogen uptake by maize ($\text{kg}\cdot\text{ha}^{-1}$) at 60 days in the 1993 glasshouse experiment

Maize P, K, Ca and Mg uptake ($\text{kg}\cdot\text{ha}^{-1}$) at 45 and 60 days of the experiment are shown in Table 7.2. Maize P and K uptake levels were significantly higher ($p<0.001$) in compost than in control and Nitram-treated maize at all rates of application, and at both stages of maize development.

Compost-treated maize showed a linear increase in both P ($p<0.05$) and K ($p<0.001$) uptake with increasing rates of application at the end of the experiment, but no significant difference was found within Nitram treatments and the control. Both maize Ca ($p<0.01$) and Mg ($p<0.001$) uptake were significantly lower in compost- compared to Nitram-treated maize at all rates of application.

Peat compost pH, which was 6.1 before experiment start, increased with compost application, tending to neutrality. The pH at the end of the experiment was approximately 5.5 for control and all Nitram treatments, 6.0 for C11 and averaged 7.2 for the rest of the compost treatments. No statistical analysis of these data was possible, as samples from all blocks were bulked together.

Table 7.2 Maize P, K, Ca and Mg uptake ($\text{kg}\cdot\text{ha}^{-1}$) at 45 and 60 days in the 1993 glasshouse experiment

Treatment	45 days from the trial start				60 days from the trial start			
	P	K	Ca	Mg	P	K	Ca	Mg
<i>cont</i>	2.4	46.3	15.1	11.5	4.8	53.6	31.8	27.7
<i>N22</i>	3.4	49.7	19.3	16.7	4.8	54.9	36.1	33.1
<i>N67</i>	3.1	45.1	18.0	16.3	2.8	33.1	27.6	22.3
<i>N112</i>	2.6	49.6	17.1	13.6	5.7	62.0	55.8	40.2
<i>C11</i>	24.8	287.3	14.5	6.2	27.5	253.2	15.7	8.6
<i>C22</i>	27.5	334.6	13.7	6.0	31.8	376.8	16.5	8.6
<i>C45</i>	31.6	361.3	13.6	6.6	38.6	481.7	14.7	9.5
<i>C67</i>	28.9	344.6	10.7	6.2	46.1	492.7	14.4	9.4
<i>C90</i>	32.8	388.2	11.2	7.7	39.6	558.6	14.4	9.9
<i>C112</i>	26.0	296.9	8.0	5.9	66.6	603.9	14.1	10.9
SED	3.00	37.10	2.32	1.84	13.05	59.90	7.66	6.89

7.1.4 Discussion

Maize N uptake levels at the end of the experiment suggest that Nitram and compost treatments were equivalent in terms of N supply to the plant. However, the compost used was old, with low levels of available N. This method of using available N as a basis for calculating the amount of Nitram equivalent to a certain amount of compost was no longer used in subsequent experiments. This was because it did not take into account the total N of compost potentially mineralised and made available during maize development (Sørensen and Jensen 1995).

Results indicate that Nitram-treated maize development was lowered due to nutrient deficiency. Potassium and nitrogen are required at the same levels by the plant, and P uptake is reduced under N deficient conditions (Pain 1978). Nitrogen supply from Nitram was adequate, as plant uptake levels indicate, but P and K were at very low levels at the two stages of assessments. Dairy manure compost supplied large quantities of both these nutrients, and 'luxury' consumption by maize occurred. The absence of P and K in the peat compost or in the mineral fertiliser caused P and K deficiency in maize, which probably limited growth.

The lower levels of Ca and Mg uptake in compost-treated maize can be explained by the high level of K in the compost. The sum of the percentage K, Ca and Mg in a plant is generally constant at all stages of growth, though considerable variation in the percentage of the individual nutrients may occur. High rates of K can result in decreased Ca and Mg absorption by plants or in Ca and Mg deficiencies (Tisdale and Nelson 1975; Pain 1978).

The best rates of nitrogen for maize development were approximately 45-90 kg N.ha⁻¹. The peak of maize dry matter production occurred at 67 N.ha⁻¹ in both compost and Nitram treatments, although no significant difference was found between all rates of the latter. There was no change in maize dry matter production at higher rates of application.

Although no statistical analysis was possible, results indicated a possible tendency of compost to increase substrate pH to neutral levels (Tester 1990).

7.1.5 Conclusions

Rates of compost application to be used in subsequent experiments should be approximately 45-90 kg N.ha⁻¹. The equivalent rates of compost in tonnes of fresh weight.ha⁻¹ should be calculated depending on the total N analysis of dairy manure compost, taking into account the potentially mineralisable N.

All major and minor nutrients should be adequately supplied in all experiments to meet maize's requirements, thus avoiding confounding the effects on plant nutrient uptake (in particular nitrogen) and dry matter production with those of nutrient deficiencies.

Compost application is particularly recommended on extreme soil pH conditions, as in acid soils, to bring pH to near neutral levels.



Plate 7.1 Maize pots at 60 days in the 1993 glasshouse experiment prior to sampling (comparison of all treatments - Table 7.1)



Plate 7.2 Layout of the 1994 glasshouse experiment A (outer maize pots are discards)

7.2 The 1994 Glasshouse Experiment A - Effects of different rates of dairy manure compost on maize (*Zea mays* L.) nutrition

7.2.1 Introduction

Previous experiments at Wye College (the 1993 glasshouse experiment, Section 7.1; and the 1993 field experiment, Chapter 4), compared dairy manure compost and inorganic N fertiliser as nutrient suppliers for maize. The results of the glasshouse experiment in relation to nitrogen supply were masked by a deficiency of phosphorus and potassium which limited maize development in the Nitram treatments. The field experiment showed very few differences in plant nutritional status between treatments, probably due to the high nutrient reserves in the soil.

7.2.1.1 Objectives

This experiment compared compost and inorganic fertilisers as nutrient suppliers (in particular of N, but also of P, K, Ca and Mg) to the maize plant in controlled conditions, and aimed to compare the results with those from the field experiments that were to be carried out during 1994 (Chapter 5).

7.2.2 Material and methods

Nine treatments (Table 7.3) were used, consisting of four rates of Nitram, four rates of dairy manure compost (equivalent to Nitram in terms of N availability) and one untreated control (with no nitrogen application). The rates were equivalent to the ones used in the 1994 field experiments (50, 100, 150 and 200 kg N.ha⁻¹), to allow a comparison of results in the field and in a controlled environment. A randomised complete block design was used with five replications (a total of 45 pots, Plate 7.2).

Peat compost, used as substrate, and dairy manure compost were analysed for nutrient composition prior to use (Appendix 3). The experiment was established and assessed as described in Section 3.4 (Chapter 3), starting on 30 April 1994. The rates of compost application were determined according to results of the total N analysis, assuming a 20% N mineralisation rate during the maize growing season (Brinton 1985).

Table 7.3 Treatments used in 1994 glasshouse experiment A

Treatment	Description	Available N (kg.ha ⁻¹)
1. <i>cont</i>	untreated control	0
2. <i>N50</i>	Nitram equiv. to 50 kg N.ha ⁻¹	50
3. <i>N100</i>	Nitram equiv. to 100 kg N.ha ⁻¹	100
4. <i>N150</i>	Nitram equiv. to 150 kg N.ha ⁻¹	150
5. <i>N200</i>	Nitram equiv. to 200 kg N.ha ⁻¹	200
6. <i>C50</i>	Compost (22 t.ha ⁻¹) equiv. to <i>N50</i>	50
7. <i>C100</i>	Compost (43 t.ha ⁻¹) equiv. to <i>N100</i>	100
8. <i>C150</i>	Compost (65 t.ha ⁻¹) equiv. to <i>N150</i>	150
9. <i>C200</i>	Compost (86 t.ha ⁻¹) equiv. to <i>N200</i>	200

In order to avoid other nutrient's deficiency, all treatments were made equivalent in P, K and Mg availability. Therefore, treatments were supplied with P and K mineral fertilisers at the necessary rates to be equivalent to the highest rate of compost application (24 kg P.ha⁻¹ and 220 kg K.ha⁻¹), which were considered adequate to meet maize's requirements (Bunting 1978). Phosphorus was supplied as single superphosphate (8.72% P, 20% P₂O₅, 18% Ca, 12% S), and K as potassium sulphate (K₂SO₄ - 43% K, 18% S). As the magnesium content of the compost was low, inorganic Mg (magnesium sulphate - 10% Mg) was applied to all treatments, at the necessary rates to supply 20 kg Mg.ha⁻¹, the total maize Mg uptake (Bunting 1978). In compost treatments, the rates of P, K and Mg application were calculated by subtracting the amounts of these nutrients present in each treatment from the total amount to be supplied. Additionally, micronutrients were added to all treatments at a standard rate (60 g.m⁻³) as Microfeed Vytel Base (chelated: Fe 3.35%, Cu 1.7%, Mn 1.7%, Zn 0.6%; unchelated: B 0.875%, Mo 320 ppm; ABM Chemicals Ltd., Stockport, Cheshire), to prevent any related deficiency that could limit maize development and interfere with nitrogen effects.

Shoot fresh and dry matter production and nutritional status were assessed at the end of the experiment, eight weeks after its start, with maize at GS 4.25 - 12/13 leaves (Groot *et al* 1986, Appendix 1). Maize nutrient uptake (kg.ha⁻¹) was calculated (Section 7.1.2).

Analysis of variance followed by orthogonal contrasts was carried out on data with Macintosh SuperANOVA GLM program (Abacus Concepts 1989).

7.2.3 Results

Fresh weight results were consistent with dry weight ones and are not presented. Nitram-treated maize had significantly higher dry matter production ($p < 0.001$) than compost-treated maize at all rates of application (Figure 7.5). However, a significant interaction ($p < 0.001$) was found between type of fertiliser and rate of application. Increasing application rates were reflected in increased maize dry matter production with Nitram- but not with compost-treated maize.

Maize N uptake was also higher ($p < 0.001$) under Nitram than under compost at all rates of application (Figure 7.6). An interaction between type of fertiliser (Nitram and compost) and rates of application ($p < 0.001$) was also found for maize N uptake (kg.ha^{-1}). Nitrogen uptake increased linearly with increasing application rates in Nitram-treated maize, but remained constant in compost-treated maize.

Maize K uptake is shown in Figure 7.7. It was significantly higher ($p < 0.001$) in compost- than in Nitram-treated maize at all rates of application. An interaction between type of fertiliser (Nitram or compost) and rate of application occurred ($p < 0.001$), as compost-treated maize showed increasing levels of K uptake ($p < 0.05$) with increasing rates of application, whereas no significant difference was found with Nitram-treated maize.

Maize uptakes (kg.ha^{-1}) of P, Ca and Mg are presented in Table 7.4. Phosphorus results were similar to those obtained for K. Phosphorus uptake was significantly higher ($p < 0.001$) in compost- than in Nitram-treated maize at all rates of application. Interactions between fertiliser type and application rates also occurred ($p < 0.001$). Compost-treated maize showed higher levels of P uptake ($p < 0.01$) with increasing rates of application, whereas no significant difference was found in Nitram-treated maize.

Calcium and magnesium uptake also showed similar results, being significantly higher ($p < 0.001$) in Nitram than in compost treatments at all rates of application. Significant interactions were also found in Ca and Mg uptake ($p < 0.001$), as there was a linear increase with increasing application rates ($p < 0.01$) in Nitram-treated maize, but no significant differences between all rates of application in compost-treated maize.

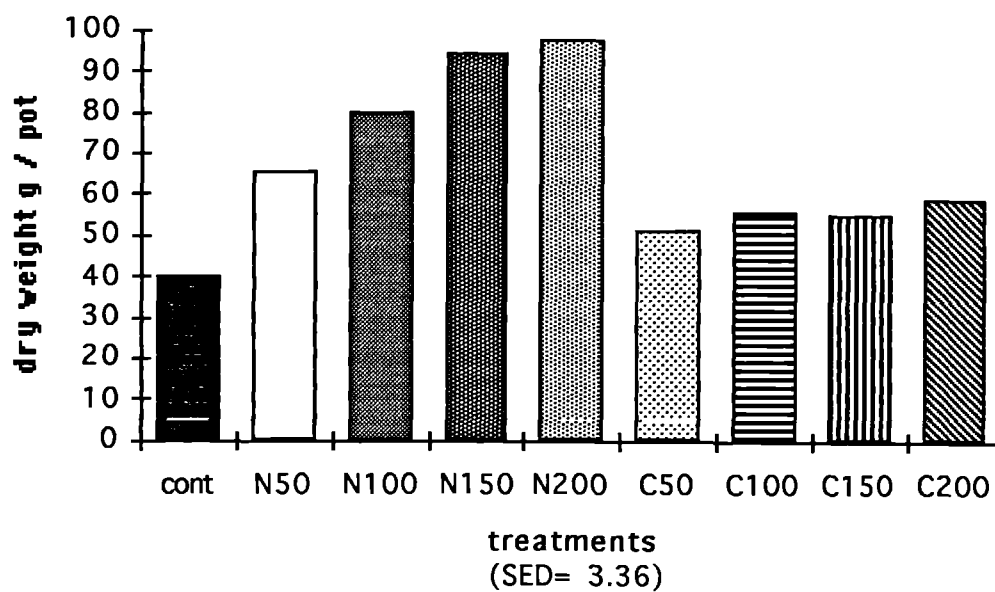


Figure 7.5 Maize dry matter production (g.pot^{-1}) in the 1994 glasshouse experiment A

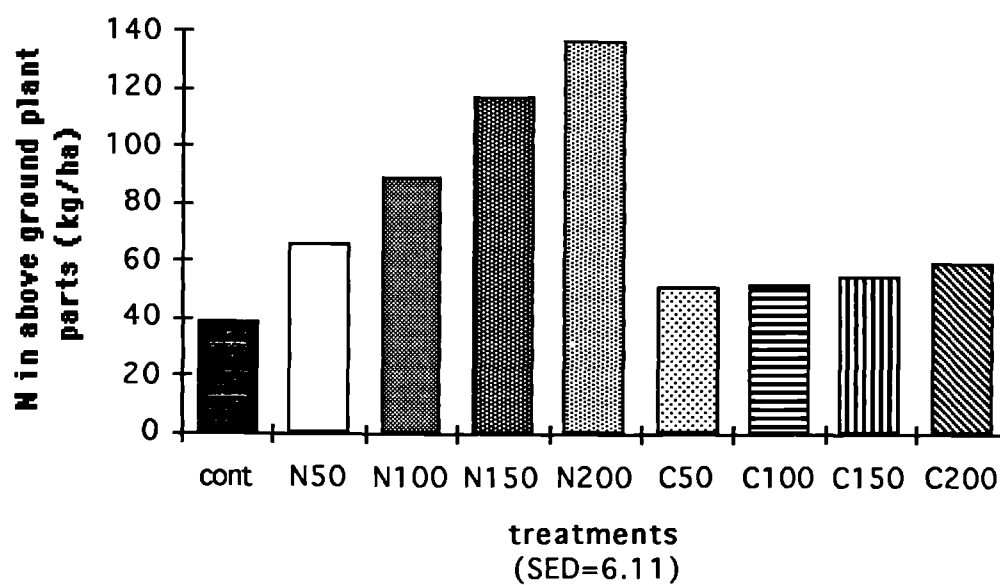


Figure 7.6 Nitrogen uptake by maize (kg.ha^{-1}) in the 1994 glasshouse experiment A

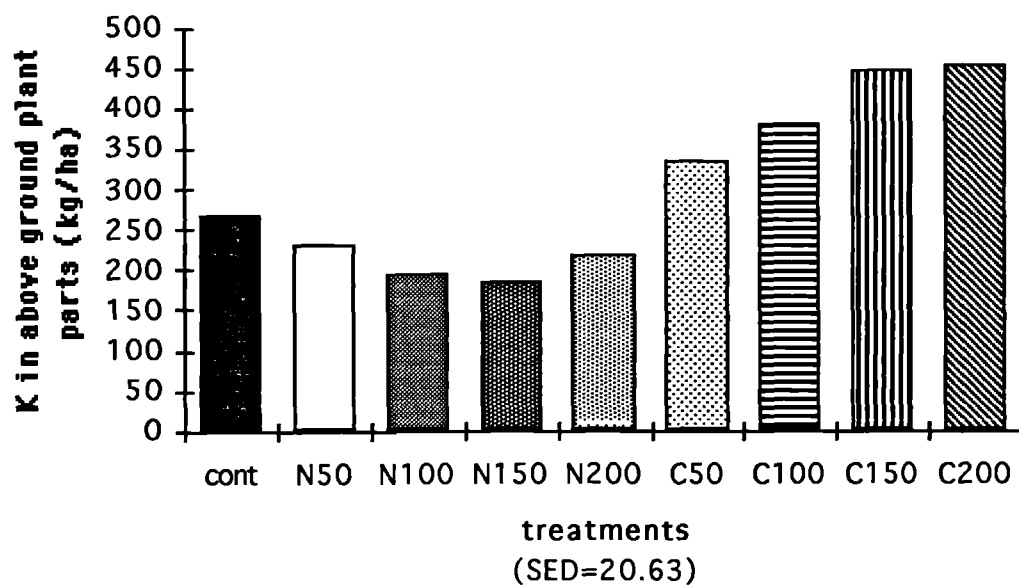


Figure 7.7 Potassium uptake by maize ($\text{kg}\cdot\text{ha}^{-1}$) in the 1994 glasshouse experiment A

Table 7.4 Maize P, Ca and Mg uptake ($\text{kg}\cdot\text{ha}^{-1}$) in the 1994 glasshouse experiment A

Treatment	Maize uptake		
	P	Ca	Mg
<i>cont</i>	15.1	29.3	12.3
<i>N50</i>	16.2	47.1	22.2
<i>N100</i>	15.0	59.2	32.0
<i>N150</i>	14.1	70.8	42.0
<i>N200</i>	16.3	78.4	45.8
<i>C50</i>	29.5	35.0	13.8
<i>C100</i>	37.7	41.5	14.8
<i>C150</i>	43.5	40.0	15.1
<i>C200</i>	49.2	42.0	17.0
SED	1.71	3.61	1.56

7.2.4 Discussion

Results indicate that compost-N was not as readily available to the plant as Nitram-N (Murwira and Kirchmann 1993). This was reflected in lower dry matter yields and lower N uptake in compost- than in Nitram-treated maize. The lower availability of compost-N could be because the actual rate of N mineralisation in compost was lower than the estimate used (from Brinton 1985). It could also be due to the short period of the experiment, as the full mineralisation potential had probably not been reached in eight weeks. Nitrogen uptake by maize is highest between flowering and early grain formation, maize GS 5-6 (Pain 1978; Groot *et al* 1986, Appendix 1). Maize was harvested at GS 4.25, before its peak for nitrogen uptake. If compost N mineralisation had continued and so coincided with maize's high demand for N, it might well have lead to both higher dry matter yields and higher N uptake.

There was no response in maize dry matter production and N uptake from increasing rates of compost application, suggesting that the lower rates should be used in field experiments. This would also decrease the volume of compost to be handled and the risks of over supply of other nutrients, such as P and K. Lower rates are also more economically efficient, decreasing the cost of production.

In the absence of data for nutrient levels in the soil/substrate after treatment application, it is not possible to assess the potential risk of nitrate pollution (through the soil water run-off) due to high rates of N application, both in Nitram- and in compost-treated pots.

Potassium and nitrogen are required at approximately the same levels by the plant, but K uptake occurs at a faster rate than N and P during the initial weeks of growth (Pain 1978). This explains the higher levels of K in comparison to N levels in maize under both compost and Nitram fertilisers. The much higher K uptake levels when compost was added indicate a 'luxury' consumption by the plant due to large quantities of this nutrient in the dairy manure compost. Calculations of rates of inorganic K application to make all treatments approximately equivalent to the C200 supply (higher rate of compost application) were based on extractable K present in the compost. Therefore, they did not account for the continuous supply of K from the organic pool of compost. Potassium is mineralised at a slow rate

and at any given moment the actual available K levels are small. But this process occurs constantly, thus the quantities absorbed by the plant tend to be replenished in the soil/substrate solution (Pain 1978).

The higher P uptake by compost-treated maize can be explained by the effect of compost application in increasing P availability to crops. Phosphate has little mobility in soil/substrate, and is easily precipitated in forms not available to plants. Dairy manure and compost application are reported to lessen fixation reactions, increasing P availability and uptake (Mazur *et al* 1983a; Tran and N'dayegamiye 1995).

The lower levels of Ca and Mg uptake in compost-treated maize are probably due to the "complementary ion effect" (Tisdale and Nelson 1975). As the sum of K, Ca and Mg percentage contents is usually constant in a plant, high levels of K uptake can result in decreased Ca and Mg absorption.

7.2.5 Conclusions

Rates of compost application to be used in field experiments in this research project should be the lowest tested (50 and 100 kg N.ha⁻¹), as no significant increase in maize biomass yields occurred at higher rates of application.

Further research is needed on mineralisation rates of dairy manure compost. Observation of growth over a longer period of time is desirable.

Mineral fertilisers have readily available N, but, with organic forms of N, higher availability occurs later. Comparisons of mineral and organic N fertilisers for maize production and N uptake should be done over a longer period, including the higher maize N demand between flowering and early grain formation.

Soil/substrate analysis should be carried out during and after maize production, to assess the potential nitrate pollution of the rates and types of fertilisers applied.

7.3 The 1994 Glasshouse Experiment B - The potential for weed infestation of dairy manure compost

7.3.1 Introduction

Weed infestation in crops is reported to increase with application of organic fertilisers such as animal manures (Doran *et al* 1987), as they often contain viable weed seeds. Therefore, weeds which were not originally present in a particular field are introduced with the organic fertiliser, contributing to lower crop yields caused by nutrient and water competition from weeds.

The high temperatures reached during the composting process are reported to kill the weed seeds present in the fresh manure, thus avoiding the risks of higher weed infestation in crops under compost application (Kiehl 1985; Ott 1990; Dalzell *et al* 1987).

7.3.1.1 Objective

This experiment is to evaluate the potential weed infestation of dairy manure compost used in the field experiments (Chapters 4-6), i.e. whether weeds may originate from viable seeds in the compost itself, rather than from the soil.

A small experiment was established in controlled conditions, comparing compost incorporated or applied as a mulch with untreated controls.

7.3.2 Material and methods

Materials are as described in Chapter 3 (without maize planting), the observations being carried out in a glasshouse. Dairy manure compost from the 1994 field experiments (Chapter 5) was used (details in Appendix 3). Eight pots received 20% dairy manure compost and 80% peat compost (w/w). In half of these pots dairy manure compost was totally mixed with peat compost, and in the other half compost was left in the surface, as a mulch. Another four pots were used as untreated controls, peat compost alone providing 100% of the substrate weight of each of the previous eight pots. A completely randomised experimental design was used.

The experiment was established in 17 July 1994, being carried out for three months. Pots were watered at approximately weekly intervals to provide ideal conditions for weed germination and growth. The results were analysed using a Chi-squared test on the presence or absence of weeds in each pot.

7.3.3 Results

After three months, all four control pots had weed infestation, indicating the possible presence of weed seeds either in the air and/or in the peat compost used as a substrate. However, weeds occurred in only 50% (two out of four) of the pots with compost incorporated and 50% of the pots with compost applied as a mulch. The Chi-squared test showed no difference in the proportion of pots containing weeds in compost and control treatments ($df=1$, $p=0.08$).

7.3.4 Discussion

The results are in agreement with mature dairy manure compost having no potential for weed infestation (Ott 1990; Dalzell *et al* 1987).

7.3.5 Conclusions

Dairy manure compost showed no potential for causing weed infestation, thus indicating that any weed seeds originally present in the fresh manure used as a raw material were killed during the composting process.

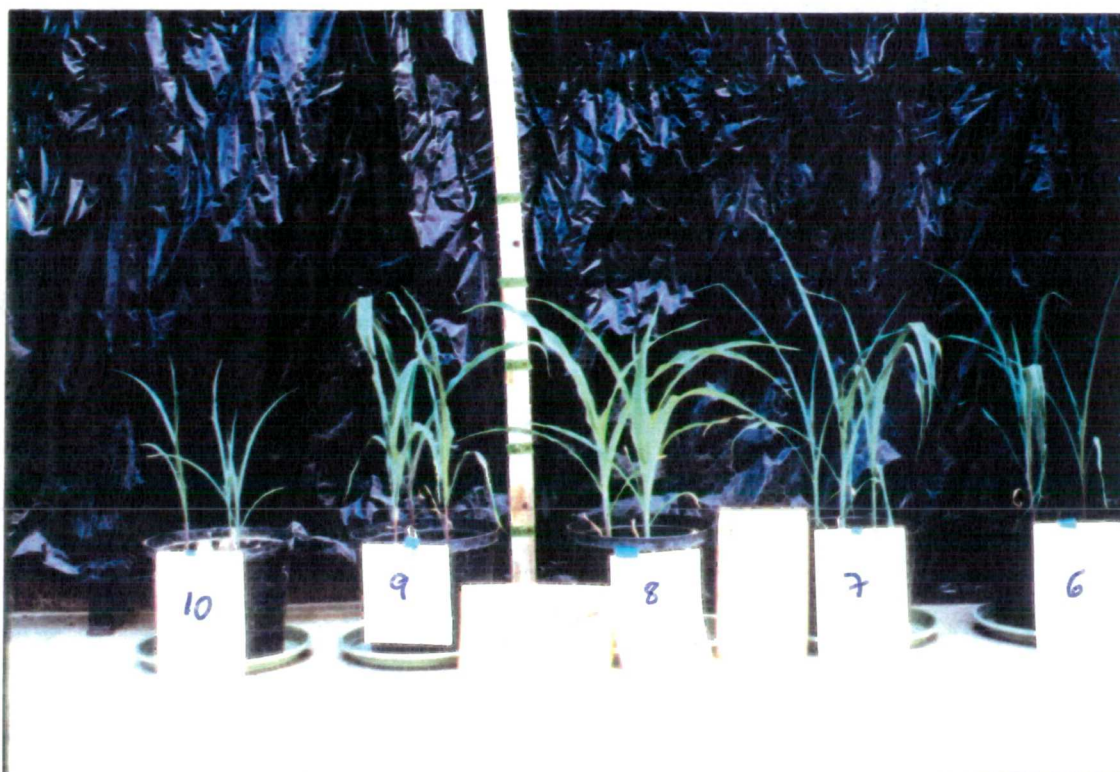


Plate 7.3 Maize pots under drought conditions at the end of the 1995 glasshouse experiment (all treatments - Table 7.5)

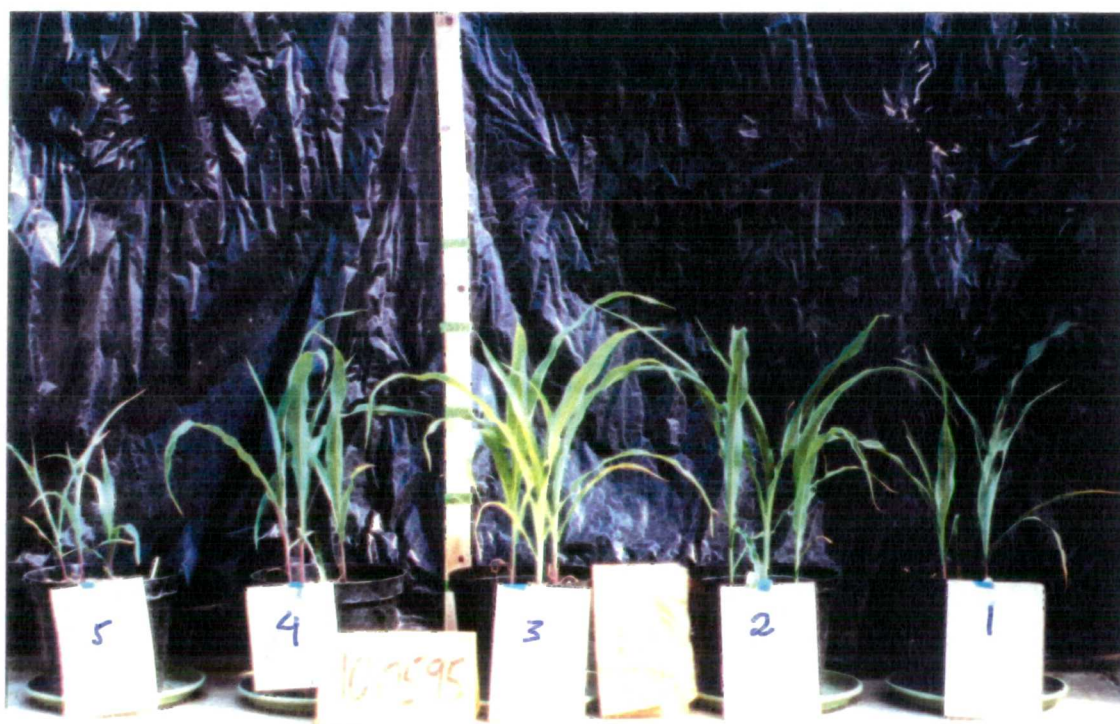


Plate 7.4 Maize pots under normal water regime at the end of the 1995 glasshouse experiment (all treatments - Table 7.5)

7.4 The 1995 Glasshouse Experiment - Effects of dairy manure compost on soil water content under maize (*Zea mays* L.) production

7.4.1 Introduction

Experiments with maize comparing dairy manure compost and inorganic fertiliser were carried out at Wye College from 1993 to 1995, both in the glasshouse (Sections 7.1-7.3) and in the field (Chapters 4-6). These experiments examined the supply of nutrients (particularly nitrogen) to maize. However, the results of the field experiments also suggested a possible effect of compost on the soil water content.

7.4.1.1 Objectives

This experiment aimed to examine the effects of compost on soil water retention under maize production, in controlled conditions.

7.4.2 Material and methods

Five additives were used. The first four were: Nitram at 100 kg N.ha⁻¹; dairy manure compost, equivalent to Nitram in terms of N availability (Brinton 1985); vermiculite, at the same volume of compost, to mimic its physical effects (no added nutrients), and one untreated control (Table 7.5). Peat compost was used as substrate (Chapter 3). The rate of N application was related to the one currently used for maize commercial production in the UK, and had also been used in the 1994 field experiments, to allow a cross comparison of results in the field and in a controlled environment. A fifth additive, consisting of soil as substrate, allowed this comparison. Soil (Appendix 2) was taken from the same field used for experiments, with no added fertiliser.

The rate of compost application was determined by the results of the N analysis (Appendix 3). The Nitram treatment was also supplied with 26 kg P.ha⁻¹, 240 kg K.ha⁻¹ and 20 kg Mg.ha⁻¹ as inorganic fertilisers (single superphosphate, potassium sulphate and magnesium sulphate, respectively, Section 7.2.2). The rates were those necessary to supply maize's total uptake (Bunting 1978). Additionally, micronutrients were added to this treatment at

a standard rate (60 g.m⁻³) as Vytel Base (Section 7.2.2) to prevent any related deficiency that could limit maize growth and interfere with other effects.

Table 7.5 Treatments used in the 1995 glasshouse experiment

Treatment number & Additive	Water Regime	Description (growing medium)	Avail. N (kg.ha ⁻¹)	Physical Effect
1. <i>cont</i>	<i>normal</i>	untreated control	0	absent
2. <i>nitram</i>	<i>normal</i>	Nitram equiv. to 100 kg N.ha ⁻¹	100	absent
3. <i>compost</i>	<i>normal</i>	Compost (70 t.ha ⁻¹) equiv. to Nitram	100	present
4. <i>vermic</i>	<i>normal</i>	Vermiculite equiv. (v/v) to compost	0	present
5. <i>soil</i>	<i>normal</i>	Soil from the <i>Orchard Field</i>	N/A	N/A
1. <i>cont</i>	<i>drought</i>	untreated control	0	absent
2. <i>nitram</i>	<i>drought</i>	Nitram equiv. to 100 kg N.ha ⁻¹	100	absent
3. <i>compost</i>	<i>drought</i>	Compost (70 t.ha ⁻¹) equiv. to Nitram	100	present
4. <i>vermic</i>	<i>drought</i>	Vermiculite equiv. (v/v) to compost	0	present
5. <i>soil</i>	<i>drought</i>	Soil from the <i>Orchard Field</i>	N/A	N/A

A split-plot experimental design was used consisting of ten treatments in six blocks (total of 60 pots). The two main plots were for plants under *drought* and those under *normal* water regimes.

The experiment was established as described in Chapter 3 (Section 3.4.1). Pots were filled with peat compost or soil. Dairy manure compost, vermiculite or nitram and other fertilisers were well mixed with peat compost, where applicable. The experiment started in 9 April 1995, with maize emerging one week later. The main plots were watered either at a *normal* (optimal) rate (350 ml of water twice at first week, and once for the next weeks), or at a *drought* rate (150 ml of water applied as in *normal*).

Plants were harvested at 30 days after planting, with maize at GS 2.50 - 5/6 leaves (Groot *et al* 1986, Appendix 1). Assessments were then made of shoot fresh and dry matter production on both water regimes.

Analysis of variance was carried out on the data, followed by orthogonal contrasts using Macintosh SuperANOVA GLM program (Abacus Concepts 1989). The two soil treatments were then excluded, and the remaining eight

treatments were further analysed according to their 2x2x2 factorial structure: the two levels of water regime (*normal* and *drought*) x the two levels of available N (0 and 100 kg N.ha⁻¹) x the two types of physical effect (present or absent).

7.4.3 Results

In general, both fresh and dry yields under *normal* water regime were higher than in *drought* conditions ($p < 0.01$, Figures 7.8 and 7.9).

The soil substrate had the lowest ($p < 0.001$) fresh and dry yields, both in *drought* and in *normal* water regimes. No significant difference was found between the two treatments without N (untreated control and vermiculite). However, both had significantly lower fresh ($p < 0.001$) and dry ($p < 0.01$) matter yields than the two treatments with 100 kg N.ha⁻¹ (Nitram and compost).

A significant interaction occurred with maize fresh yield between physical effect and water regime ($p < 0.05$, Figure 7.10). In *drought* conditions, the average fresh weight of treatments with a physical effect (compost and vermiculite) was higher than of the treatments without a physical effect (control and Nitram), with compost-treated maize showing the highest fresh biomass yield ($p < 0.01$, Figure 7.8). But in the *normal* water regime the opposite pattern occurred, with Nitram-treated maize having the highest fresh yield ($p < 0.01$, Figure 7.8). However, fresh biomass yields were not significantly different between compost and Nitram treatments in general.

The higher fresh yields in *drought* conditions for the average of both treatments with physical effect was not reflected in higher dry matter yields. In *drought* and in *normal* water conditions, the average dry yields of control and Nitram (both treatments without a physical effect) was significantly higher ($p < 0.05$, Figure 7.11) than the average of compost and vermiculite (both treatments with a physical effect). In both water regimes, Nitram-treated maize had a higher dry matter production than control, vermiculite and soil treatments ($p < 0.05$, Figure 7.9), but was not significantly different from compost-treated maize.

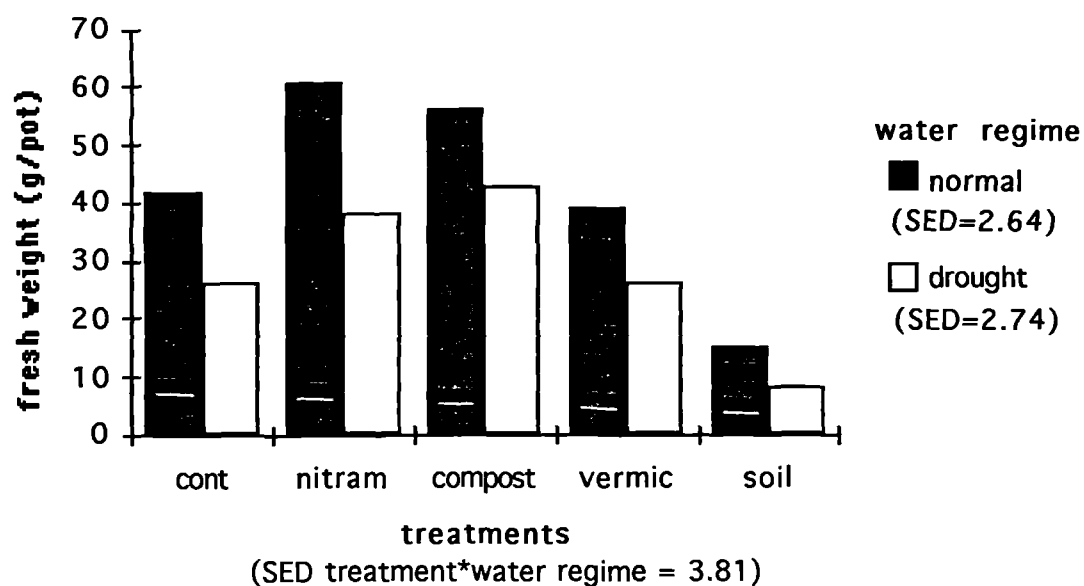


Figure 7.8 Maize fresh biomass production (g.pot⁻¹) in the 1995 glasshouse experiment

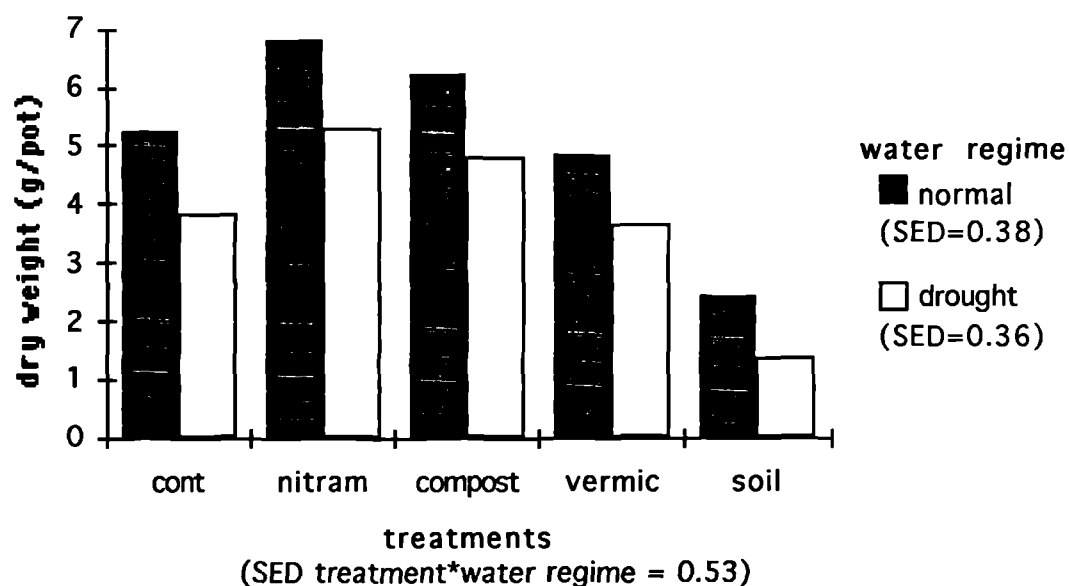


Figure 7.9 Maize dry matter production (g.pot⁻¹) in the 1995 glasshouse experiment

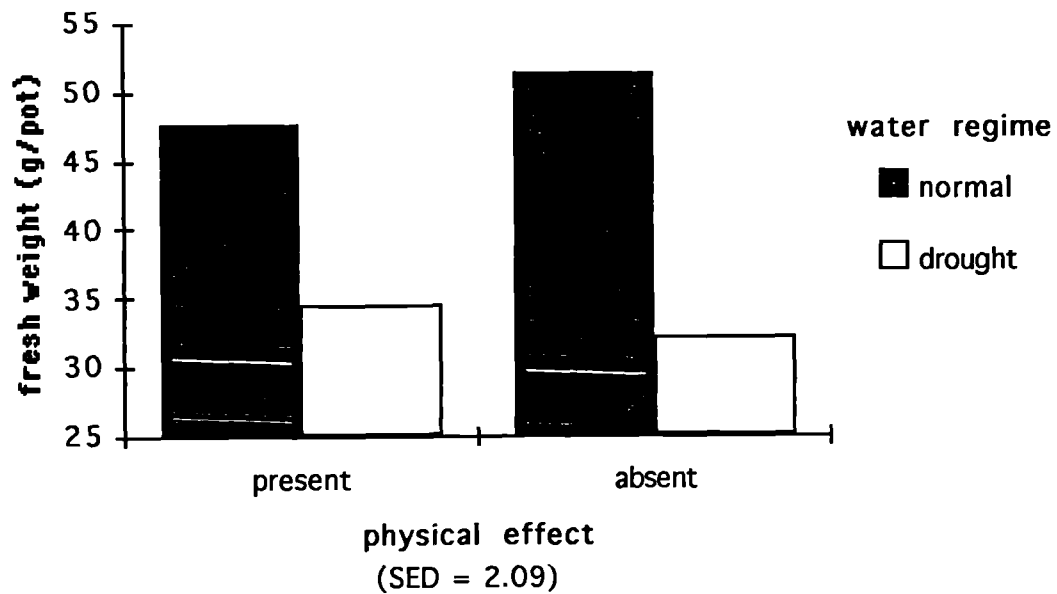


Figure 7.10 Interaction in maize fresh biomass production (g.pot^{-1}) between physical effect and water regime in the 1995 glasshouse experiment

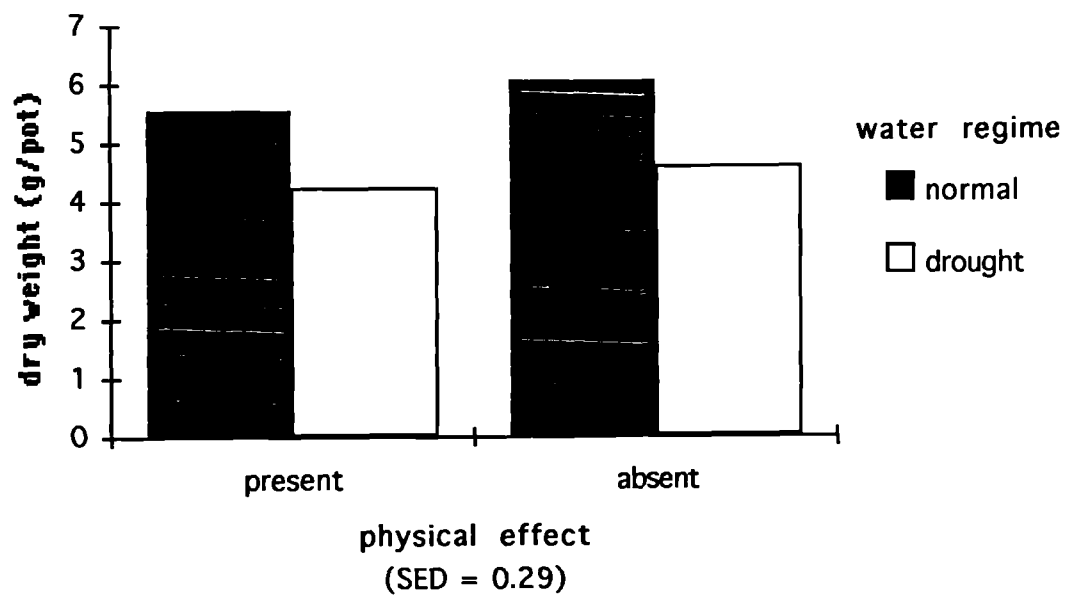


Figure 7.11 Interaction in maize dry matter production (g.pot^{-1}) between physical effect and water regime in the 1995 glasshouse experiment

All maize plants were very wilted under *drought* conditions at the end of the experiment with the exception of compost-treated pots. However, the latter had a lighter green colour than the Nitram-treated plants in both *drought* and *normal* water regimes (Plates 7.3 and 7.4).

7.4.4 Discussion

Maize was clearly affected by drought, as shown by the reduced crop fresh and dry matter yields in all *drought* treatments.

Higher fresh biomass yields in the average of compost and vermiculite than in the average of Nitram and control treatments indicate the potential for higher yields from compost in drought conditions, probably due to its physical effect in enhancing moisture retention (Sahs and Lesoing 1985; Uson and Cook 1995). However, the critical period for a water shortage effect on maize yields is from 30 to 40 days either side of the flowering stage (Rouanet 1987), and the present experiment was finished before this critical period had been reached. Higher differences in yields from compost-treated maize would be expected if the experiment ran over a longer period of time.

Lower fresh and dry matter yields in the soil treatments were probably due to a combination of nutrient deficiency and physical properties. No nutrients had been added to the soil, vermiculite and control treatments. However, the peat compost used as a substrate in the two latter treatments had better water retention capacity than the soil, resulting in higher yields. Furthermore, the soil was disturbed when taken from the field and put into pots, probably resulting in worse physical conditions than originally in the field, such as compaction, loss of porosity, less aeration and infiltration which may have impaired root development. Hence, results obtained under these conditions were not suitable for comparison with field experiment results.

The potential physical effect of vermiculite and compost treatments was reduced when used with peat compost as a substrate, which had high water holding capacity. Nevertheless, plants were visibly less wilted (Plate 7.3) under vermiculite and compost treatments than under control, Nitram and soil treatments in *drought* conditions. Results indicated that in drought conditions the physical effect of compost increases water availability to plants, leading to higher fresh yields. However, these results were probably

due only to a higher water content in the plant, and not to the production of dry matter, as these higher fresh yields were not reflected in higher dry yields. This might have occurred if the substrate used had a lower water holding capacity, thus increasing the beneficial physical effect of compost and vermiculite.

Treatments with available N had higher fresh and dry yields than treatments without N application, clearly indicating that the nutrient effect was the more important factor in dry matter production in the conditions of this experiment. However, the lighter green colour observed in maize leaves of compost-treated maize is a symptom of N deficiency (Pain 1978; Marschner 1986), suggesting that the compost-N was not as available to plants as the Nitram-N, although both should be supplying 100 kg N.ha⁻¹. This could be due to the short period of the experiment, as the mineral N of Nitram was readily available, but the compost-N was mainly in the organic form, thus requiring some time to mineralise.

7.4.5 Conclusions

Maize production is greatly decreased in drought conditions.

Under drought conditions, crop fresh biomass yields are potentially higher under compost than under mineral fertilisers, due to the added physical effects of compost in increasing water availability to plants.

Nutrient availability is the limiting factor in maize dry matter production even under below optimum water supply, although water availability might be crucial under more extreme dry conditions.

In the short-term, with the calculated equivalent rates of N application, compost-N is less available to plants than Nitram-N, as the N mineralisation process of the former occurs gradually, whilst Nitram-N is already in the mineral form.

Chapter 8. The 1995/96 Laboratory Experiment

8.1 Nitrogen mineralisation rates of dairy manure compost applied to different soils under controlled conditions

8.1.1 Introduction

8.1.1.1 *Objectives of the laboratory experiment*

This experiment followed field and glasshouse experiments carried out in Wye, from 1993 to 1995 (Chapters 4-7), which compared dairy manure compost and inorganic fertiliser (Nitram) as nutrient suppliers for forage maize (*Zea mays* L.).

Brinton (1985) and Brinton and Seekins (1994) estimated that 15-20% of the total N of composted dairy manure was mineralised during the growing season of maize, in field conditions. These figures were used as a basis for calculating the amount of compost applied in field and glasshouse experiments, to ensure that both compost and Nitram applied were approximately equivalent in terms of N availability.

The objective of this experiment was to study N mineralisation rates of dairy manure compost under controlled conditions, in order to understand better the results of the past experiments in terms of N supply to the crop.

8.1.1.2 *Nitrogen transformation processes*

Nitrogen mineralisation is the process in which organic forms of nitrogen are reduced into inorganic forms and thus made available for crop use. Usually, the immediate product of nitrogen mineralisation of organic N forms is ammonium (NH_4^+) by the process of ammonification, which in turn may be converted to nitrate (NO_3^-) by the process of nitrification, depending on the presence of adequate microorganisms and the redox conditions (Brown 1982).

When soil samples are incubated with or without an organic amendment, the changes measured in NH_4^+ and NO_3^- concentrations indicate the rate of nitrogen mineralisation. The rate may be negative, suggesting that the

amount of nitrogen mineralised is lower than the amount assimilated by plants, immobilised by microorganisms, or lost by leaching, denitrification or volatilisation processes (Brown 1982).

Immobilisation occurs following a high C/N ratio (>30) input to soil, when microorganisms will take all available N to combine with the excess C of the substrate, in the synthesis of amino acids and proteins (Bartholomew 1965). Denitrification and volatilisation are gaseous losses of nitrogen transformed from NO_3^- and NH_4^+ , respectively, occurring under anaerobic conditions or at high pH levels (Harris 1988).

The soil moisture level, aeration, pH, texture, depth and temperature, as well as the size and nature of organic residues, other nutrients' levels and the presence of anti-microbial agents all have a direct influence on microbial activity and hence on mineralisation rate (Stanford and Smith 1972; Cassman and Munns 1980; Brown 1982). Furthermore, indices of N availability from composted manures added to soil vary widely, depending on the total N content, C/N ratio, and degree of maturity of the compost, along with the soil characteristics (Hébert *et al* 1991).

The mineralisation rate is not a linear function of time, and it is difficult to interpret the data from long-term incubation experiments. Nevertheless, attempts to measure the mineralisation processes of compost in soil aim at obtaining information on nitrogen availability for a crop during its growing season, allowing a more efficient strategy on the use and application of compost (Brown 1982).

8.1.2 Material and methods

The aerobic incubation method of Stanford and Smith (1972) was used to determine N mineralisation rates, with some modifications (Cassman and Munns 1980). Two soil types with different characteristics were used (Table 8.1; further details in Appendix 2), to allow a better understanding of the mineralisation processes, as affected by compost-soil interactions.

The first soil, named UK soil, was taken from *Orchard Field*, on Wye College Estate, UK, where the field experiments from 1993 to 1995 were conducted. It was a rich soil, with high organic matter content. The second soil, named Brazil soil, was shipped to Wye in 1990, and kept under ambient conditions

prior to the experiment. It was a highly weathered soil, with poor fertility and low organic matter content. The high acidity also contributed to fertility deficiency, due to chemical fixation of certain nutrients in unavailable forms (Giller and Wilson 1991). The UK soil was previously under barley cultivation, and the Brazil soil was under pasture.

Table 8.1 Characteristics of the soils used in laboratory experiment

Soil type	Origin	Description	pH	C(%)	OM(%)	N(%)
1. Coombe series ¹	<i>Orchard Field</i> , Wye, UK	moderately deep phase, brown, calcareous silt loam ³ (22.6% clay, 56.8% silt, 20.6% sand)	8.0	1.7	4.5	0.16
2. Oxisols ²	<i>Cerrado</i> region, Brazil	deep phase, dark- red, very well drained sandy clay loam ³ (35.8% clay, 12.8% silt, 51.4% sand)	5.2	1.2	1.5	0.10

¹Soil Survey of England and Wales (Green and Fordham 1973)

²USDA classification (Resck *et al* 1991)

³USDA classification (Avery 1990)

Dairy manure compost was the same as that used in Wye field experiments in 1995. It was a mature compost, with pH 8.7, 2.78% of total N, 35% of dry matter content, and a C/N ratio of 10 (further details in Appendix 3).

Samples of both soils, 0-20 cm deep (plough-depth), were taken from unfertilised soil, air dried and put through a 2 mm-sieve. Soil was mixed with 40-mesh silica sand 1:2 (wt/wt soil:sand air dried mass basis, with 50 g of soil and 100 g of sand in each leaching tube) to improve drainage. The sand had been purified by acid (HCl 10%) for 48 hours, and subsequently washed with de-ionised water to reach pH 7.0.

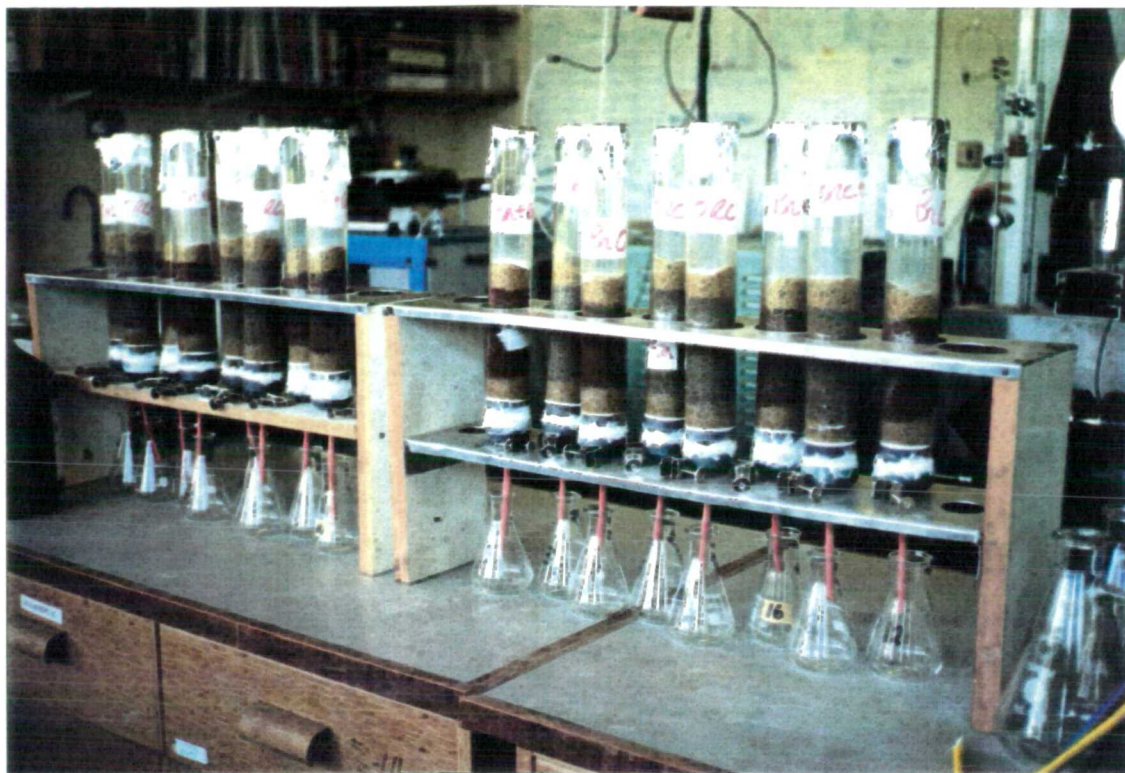


Plate 8.1 Leaching tubes in the 1995/96 laboratory experiment (solution is poured into tubes and collected for N mineralisation rates determination)



Plate 8.2 Vacuuming to remove excess solution from soil in leaching tubes. Drainage stems are then closed and tops covered to avoid moisture loss.

Part of each soil was thoroughly mixed with dairy manure compost, at rates equivalent to 50 t fresh weight.ha⁻¹ (100 kg N.ha⁻¹), and another part was left untreated, as control soils (Table 8.2). Four replicates were used, in a RCB design with a 2x2 factorial structure: the two soil types (UK and Brazil) x two amounts of compost (0 and 100 kg N.ha⁻¹), in a total of 16 leaching tubes.

Table 8.2 Treatments used in laboratory experiment

Treatment	Description	Available N (kg N.ha ⁻¹)
<i>UK0</i>	UK soil untreated	0
<i>UKC</i>	UK soil with compost application	100
<i>Br0</i>	Brazil soil untreated	0
<i>BrC</i>	Brazil soil with compost application	100

In the base of each leaching tube (Plexiglas, 25 cm long x 3 cm internal diameter), a plastic bung fitted with a drainage tube was placed, topped by a perforated plastic ring. A thin glass wool pad (G/FA filter) was placed over this to prevent soil losses during leaching, and a 40 g layer of 40-mesh silica sand poured on top. Then, the soil-sand mixture, with and without compost, was transferred into the tube. A further 40 g layer of silica sand was poured on top, with another thin glass wool pad over it, to avoid disturbance of the soil surface when the solution was being poured into the tube (Plate 8.1).

Mineral N initially present was removed by leaching with 150 ml of dilute nutrient solution (1.0 mM CaCl₂, 1.0 mM MgSO₄, and 1.0 mM KH₂PO₄), in 50 ml increments. Excess solution was removed with the use of 250 ml side-arm Erlenmeyer flasks attached to a vacuum system (0.24 bar matric suction), leaving the samples' moisture content at 50% (Plate 8.2). The drainage stems of tubes were then closed, to prevent loss of moisture. The tops were covered with aluminium foil. Gas exchange with the atmosphere was facilitated by making two pinholes in the foil, to ensure aerobic conditions. Tubes were incubated in the dark at 28°C, starting on 14 August 1995.

Mineralised N was recovered from each tube after 1, 3, 5, 7, 9, 12, 15, 22 and 28 weeks of incubation, by leaching with 100 ml of diluted nutrient solution in 50 ml increments. Leachates were then analysed for NO₃-N and NH₄-N

(Chapter 3). After each leaching, each sample's moisture content was restored to 50% by suction. Loss of moisture was negligible during incubation.

A SAS GLM procedure (with repeated measures analysis of variance to detect differences in trends over time) was used for the statistical analysis of data (SAS 1989). As the block effect was not significant for any variable, it was removed from the analysis to increase the residual degrees of freedom.

The net mineralisation of compost N was determined by subtracting the amount of N mineralised in each control soil from the amount mineralised in the respective compost-amended soil (e.g. $\text{NO}_3\text{-N}$ level in *UKC* - $\text{NO}_3\text{-N}$ level in *UK0* = compost N mineralised in UK soil). In this way, the contribution from soils was removed from the final results (Kirchmann 1991). A *t*-test was used for the comparison of these means at selected dates.

8.1.3 Results

Negligible amounts of $\text{NH}_4\text{-N}$ were recovered from leachates of all samples throughout the incubation period. Hence, nitrogen mineralisation rates of compost were indicated by the $\text{NO}_3\text{-N}$ levels recovered from leachates. Compost N mineralisation rates, expressed as a percentage of the amount of total compost N initially added to each soil, are presented in Figures 8.1 and 8.2. The same results expressed as the amount of N mineralised per unit of fresh weight of compost added to soil are shown in Figures 8.3 and 8.4.

The soil type had a clear effect on compost N mineralisation rates. Although no significant difference occurred in N availability between both soils in the first week of incubation, net mineralisation trends were visibly different thereafter (Figures 8.1 and 8.3). When applied to the Brazil soil, compost had a faster N mineralisation, as indicated by a greater level of $\text{NO}_3\text{-N}$ from week 3 of incubation, which steadily decreased towards the final stages. An opposite pattern was observed when compost was added to the UK soil. This was confirmed by a significant difference ($p < 0.01$) in N availability at both week 3 and week 22 between soils.

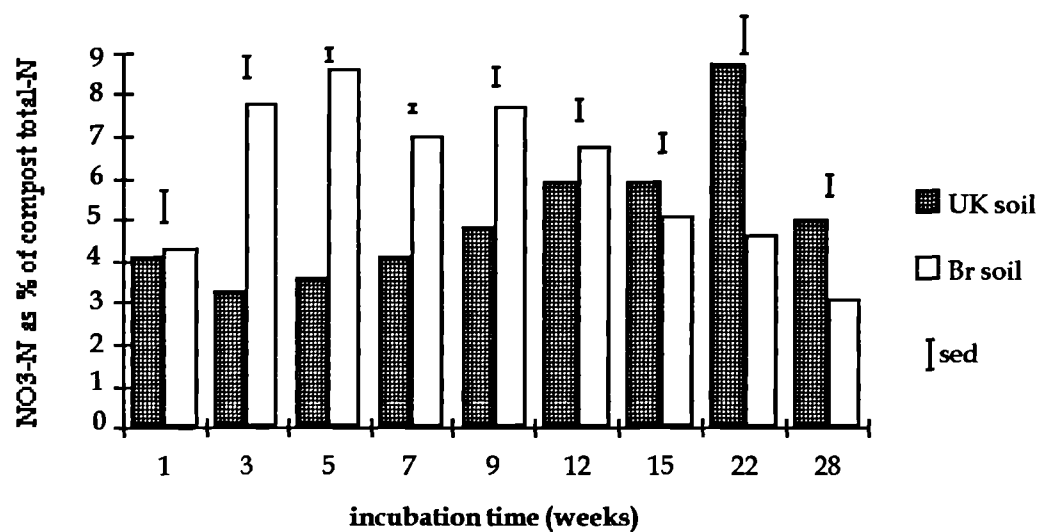


Figure 8.1 Net N mineralised at each sampling date from compost ($\text{NO}_3\text{-N}$ as % of compost total N) applied to two soils (1995/96 laboratory experiment)

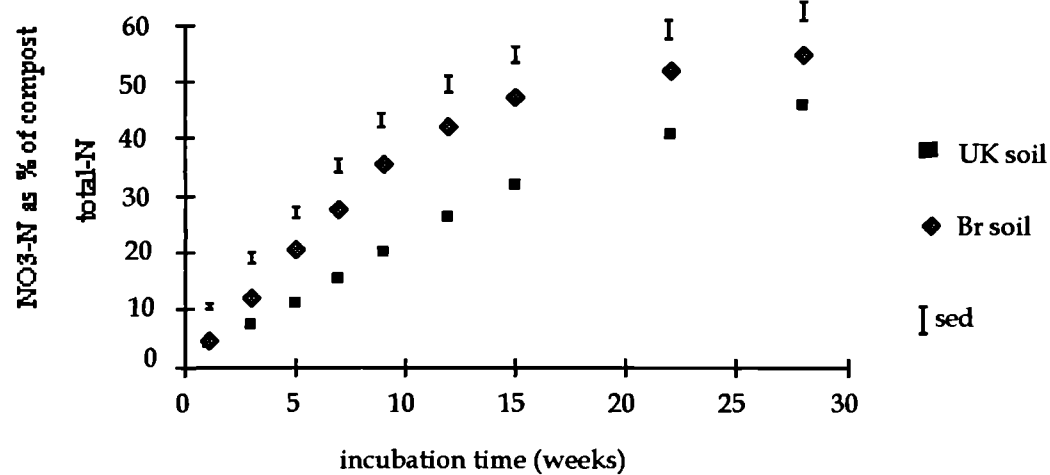


Figure 8.2 Cumulative net N mineralised from compost ($\text{NO}_3\text{-N}$ as % of compost total N) applied to two soils (1995/96 laboratory experiment)

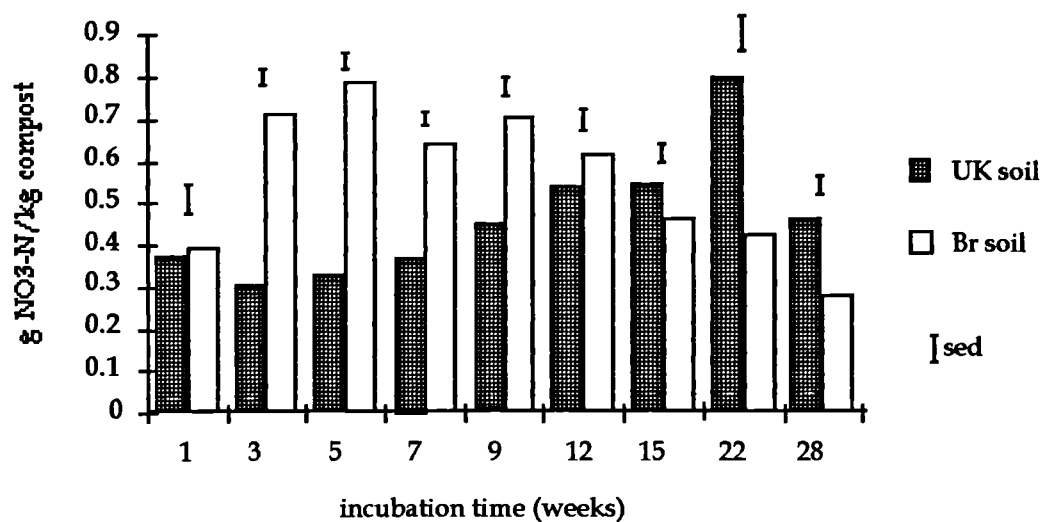


Figure 8.3 Net N mineralised from compost (g NO₃-N.kg⁻¹ fresh weight compost) applied to two soils, at each sampling date (1995/96 laboratory experiment)

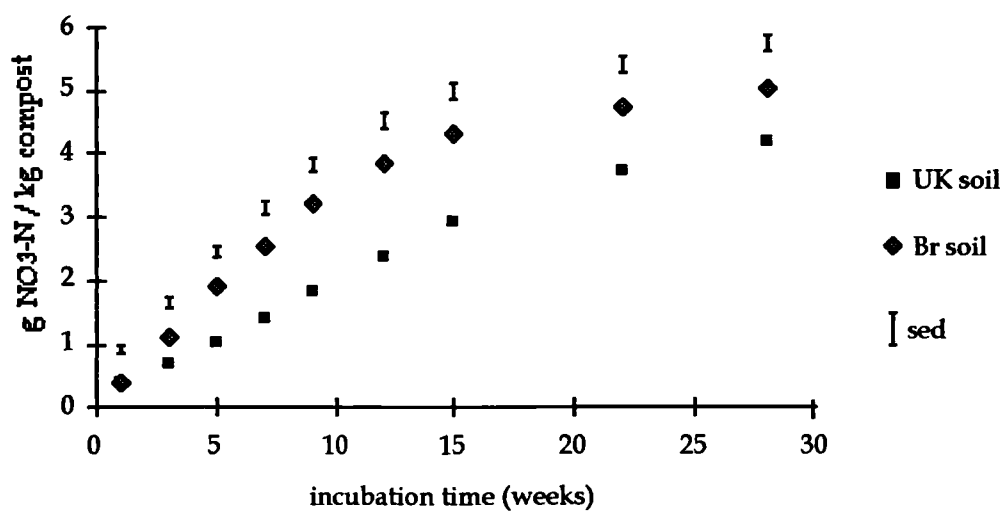


Figure 8.4 Cumulative net N mineralised from compost (g NO₃-N.kg⁻¹ fresh weight compost) applied to two soils (1995/96 laboratory experiment)

The faster compost N mineralisation in the Brazil soil was also evident when $\text{NO}_3\text{-N}$ release was accumulated over incubation time (Figures 8.2 and 8.4), with a significantly steeper linear trend in the Brazil soil curve ($p < 0.05$). Distinct mineralisation kinetics of compost N in the two soils was further indicated by the very significantly different quadratic ($p < 0.001$) and cubic ($p < 0.001$) trends followed by the curves.

The amount of accumulated compost N mineralised was significantly greater in the Brazil soil throughout the incubation period ($p < 0.001$), other than in the first week. After five weeks, 11% of total compost N was already mineralised in the UK soil, but almost twice as much (20%) was mineralised in the Brazil soil (Figure 8.2). Although this difference narrowed progressively towards the final stages of incubation, a still significantly higher rate of compost N mineralisation ($p < 0.01$) was found in the Brazil soil after 28 weeks (45% and 55% respectively, for the UK and the Brazil soil).

From Figure 8.4, with the application of 50 t.ha^{-1} of fresh weight compost, approximately 120 kg of crop available nitrogen (as $\text{NO}_3\text{-N}$) per hectare would be released in the UK soil after 12 weeks ($2.4 \text{ g NO}_3\text{-N} \times 50 \text{ t.ha}^{-1}$), under optimal mineralisation conditions, whereas $190 \text{ kg NO}_3\text{-N.ha}^{-1}$ ($3.8 \text{ g NO}_3\text{-N} \times 50 \text{ t.ha}^{-1}$) would be available in the Brazil soil.

8.1.4 Discussion

Results of incubation experiments are evaluated presupposing that no gaseous losses occur during incubation either by ammonia volatilisation or by nitrate denitrification. Therefore, the measurements of inorganic N over time are assumed to reflect the net mineralisation or immobilisation patterns of compost in soil (Kirchmann 1991). The absence of negative mineralisation rates throughout the incubation period indicates that only net mineralisation occurred.

Soil moisture, aeration and temperature of incubation were considered optimum for N mineralisation, and, along with sampling depth, were similar in both soils (Cassman and Munns 1980; Brown 1982). Soil pH from both soils was within the range from 5.5 to 8.0, considered optimum for nitrification processes (Schmidt 1982). Cassman and Munns (1980) also found negligible amounts of $\text{NH}_4\text{-N}$ being recovered from leachates

throughout the incubation period. This indicates that ammonium levels in aerated soils are generally negligible during plant growth.

A consistently higher amount of N was released from compost in the Brazil soil than in the UK soil, probably due to the higher sand content of the former. The UK soil was a fine silty loam with moderate clay content and poor drainage, as indicated by previous difficulty experienced in leaching the soil (Rodrigues 1996). Similar results were reported by Sørensen (1975), Amato and Ladd (1992), and Rubaduka *et al* (1993), with faster mineralisation occurring in sandy than in clay soils. According to Sørensen (1972), both the amount and the composition of clay minerals may influence the turnover of organic compounds. Sørensen (1975) concluded that highly adsorptive clay soils retain far more microbial biomass and metabolites formed during the initial phase of the decomposition process. These results indicate that plant availability of compost N during the initial weeks after application is higher in sandy than in clay soils, considering similar losses.

Moreover, the organic matter content was much higher in the UK soil (4.5%) than in the Brazil soil (1.5%). Nitrogen compounds are reported to resist degradation when complexed with humic and humic-like materials present in the soil organic matter (Brown 1982), further explaining the lower mineralisation rates in the UK soil.

The mineralisation levels of 45% and 55% of compost N respectively, in the UK and the Brazil soils, after 28 weeks of incubation, were much higher than the 15-20% estimated by Brinton (1985) and Brinton and Seekins (1994), based on N uptake by maize. However, those levels were estimated to be made available during a maize growing season under field conditions. Comparisons of results obtained at the laboratory and in the field should be treated with caution, taking into account their different conditions.

The results presented here clearly oppose those of Murwira and Kirchmann (1993), who found net immobilisation and very low amounts of N mineralised from aerobically decomposed manure (-3 and 3.5% respectively, in a silt loam and a sand soil, after 8 weeks of incubation). They reported on results found by Chae and Tabatabai (1986), where only 1.4% of fresh manure organic N was mineralised after 8 weeks, although the figure increased to 13% in a silty soil after a long-term incubation period of 28 weeks. Sørensen and Jensen (1995) found that 18% of a fresh sheep manure

N was mineralised after 84 days of incubation at 20°C with a soil-sand mixture with low clay content (4%). Castellanos and Pratt (1981) detected low N mineralisation of 5-8% organic N in composted dairy manure after incubation with a sand soil for 10 weeks, although fresh dairy manure reached levels around 20%. Kirchmann (1991) reported net N mineralisation of 5-9% of the total N of fresh cattle and pig manure, incubated with a calcareous silt loam soil in a 2-month experiment at 25°C and optimal moisture level, and only 1-4% from aerobically decomposed manures.

However, higher rates of N mineralisation were also found in the literature. Hébert *et al* (1991), referring to previous studies, reported on net N mineralisation rates of 28% of total compost N after 10 weeks of aerobic incubation. Rodrigues (1996), working with similar British and Brazilian soils used in the present experiment, found that about 15% and 55% respectively, of the total N of farmyard manure compost were mineralised in these soils after 12 weeks of incubation.

It is not easy to interpret N mineralisation rates, as complex soil-compost interactions occur together with mineralisation-immobilisation processes (Hébert *et al* 1991). Moreover, in field experiments, the presence of plants and uncontrolled conditions, such as soil temperature and moisture levels, greatly influence N mineralisation. In the laboratory, both soil temperature and moisture were maintained at optimum levels for the mineralisation processes. Thus, compost N mineralisation was faster there than under field conditions. It is important to bear these different conditions in mind when trying to extrapolate results obtained in laboratory experiment to field conditions. Comparisons of the conditions of this laboratory experiment and those carried out in the field from 1993 to 1995 are made in Chapter 9. A relationship between the results obtained under both field and laboratory conditions in this research project is attempted in Chapter 10.

However, the results presented in this chapter indicate that compost has a great potential to continuously supply adequate amounts of readily available N to crops, particularly in tropical regions, with optimal mineralisation conditions.

8.1.5 Conclusions

Nitrogen mineralisation rates are lower in soils with high organic matter content.

Availability of compost nitrogen to plants is higher in sandy than in clay soils, considering similar losses, as the mineralisation process is faster in the former than in the latter.

Compost as a fertiliser has the potential to supply adequate amounts of available N to crops, particularly with optimal mineralisation conditions.

Comparisons of mineralisation rates obtained in the laboratory and in the field should be made with caution, taking into account their different climatic conditions, and that complex soil-compost-plant interactions occurring in the latter can highly influence the mineralisation process.

Chapter 9. Comparison between Climatic Conditions in Experiments

9.1 Introduction

In this research project, field and glasshouse experiments were carried out at Wye College Estate, UK, from 1993 to 1995 (Chapters 4-7), studying the use of dairy manure compost for sustainable maize production. Additionally, a field experiment was carried out in Viterbo, Italy, during 1995 (Chapter 6). These field experiments enabled the examination of the extent to which results could be generalised over several growing seasons, and the comparison of some of the results under different weather conditions. A further experiment was carried out in the laboratory in Wye (Chapter 8), looking at the mineralisation rates of compost nitrogen.

Detailed meteorological data during 1993-1995 in Wye, and a comparison between temperature means and total rainfall in Wye and in Viterbo during 1995 are presented in Appendix 9. This chapter aims to summarise the seasonal variations between field experiments in Wye and Viterbo, and the differences between these and the controlled glasshouse and laboratory environment, to enable results obtained in all experiments to be compared.

9.2 Temperature

9.2.1 Seasonal variations between field experiments

In general, few differences occurred in the maximum temperatures means between the three growing seasons in Wye (Table 9.1). Nevertheless, temperatures tended to be lower during April and May in 1994 than in 1993 and 1995. Between July and September, temperatures were higher in 1995 than in the other two growing seasons, being lowest in 1993.

As expected, considerable differences in temperature occurred between Wye (1993-1995) and Viterbo (1995; Table 9.1), the latter showing higher values throughout the growing season. October values are not presented in 1995, as maize was harvested in September both in Wye and in Viterbo.

Table 9.1 Monthly maximum temperature means (°C) during the 1993-1995 field experiments in Wye and in Viterbo (1995 only)

month	Wye			Viterbo
	1993	1994	1995	1995
April	13.7	11.7	13.3	16.2
May	17.2	15.0	17.2	19.8
June	20.0	19.8	18.1	25.0
July	20.5	23.7	24.1	32.0
August	20.6	21.6	24.7	27.8
September	16.6	17.1	18.1	23.2
October	12.4	13.6	n/a	n/a

Accumulated effective temperature is more useful for comparisons between growing seasons. The effective daily temperature relates to the length of time that the daily temperature is above a base temperature (usually taken to be 10°C), which is considered to be the minimum required for maize growth and development. Assuming that temperature is the main factor determining maize rate of development, the accumulated effective temperature between these developmental stages is similar for different sites and seasons (Carr and Hough 1978).

The Ontario system is considered one of the most accurate methods of accumulating temperatures for comparisons between different seasons and different areas of maize growth (Carr and Hough 1978). Figure 9.1 shows the cumulative Ontario Units (OU)¹ from maize drilling in the 1993-1995 field experiments in Wye. The meteorological data necessary for the effective temperature calculation in Viterbo are not available, hence its comparison with Wye using accumulated temperature is not possible.

In England, seasonal totals of 2300-2500 OU are necessary for forage maize to reach a 25-30% DM content at harvest (Carr and Hough 1978). These totals were achieved by October in 1993 and 1994, and by September in 1995.

¹ Ontario Units = 0.5 (Y_{max} + Y_{min})

where Y_{max} = 3.33 (T_{max} - 10) - 0.084 (T_{max} - 10)² when T_{max} < 10, Y_{max} = 0

Y_{min} = 1.8 (T_{min} - 4.4) when T_{min} < 4.4, Y_{min} = 0

T_{max} and T_{min} are daily maximum and minimum temperatures, respectively

In 1993, accumulation of heat units was faster from the start (May) to the end of June (approximately 50 days after drilling), decreasing thereafter. Comparatively, OU accumulation started slowly in 1994 and 1995, but increased considerably from the end of June until mid-August (approximately from 50 to 100 days after drilling), remaining high in 1995 until early September, when the crop was harvested.

9.2.2 Relation between maize developmental stages and accumulated heat units

A general relationship between maize Growth Stages (GS; Appendix 1), and the accumulated temperature was developed by Groot *et al* (1986; Figure 9.3). It uses a simpler method for defining effective daily temperature, by subtracting a base temperature from the daily mean². Positive values from plant emergence are accumulated in day-degrees (day°C) between prescribed GS. Approximately 675 day°C are required for early European maize hybrids to reach a 25% DM content at harvest (Bunting 1978).

Through the respective accumulated temperature, it is possible to compare approximate maize GS (Appendix 1) in the field experiments in Wye (1993-1995) and in the glasshouse (1993-1995 mean; Figure 9.4).

9.2.3 Comparisons between field, glasshouse, and laboratory conditions

Unlike in the field conditions, the accumulation of heat units in both glasshouse and laboratory environments was relatively constant, as the temperature was controlled. This resulted in a greater rate of OU accumulation under both controlled conditions than in the field (Figure 9.2). Accumulation of OU was fastest in the laboratory environment, as temperatures were higher there than in the glasshouse.

² $T_{\text{eff}} = 0.5 (T_{\text{max}} + T_{\text{min}}) - T_b$

where T_{eff} is effective daily temperature ³ 0

T_b is base temperature = 10°C

T_{max} and T_{min} are daily maximum and minimum temperatures, respectively

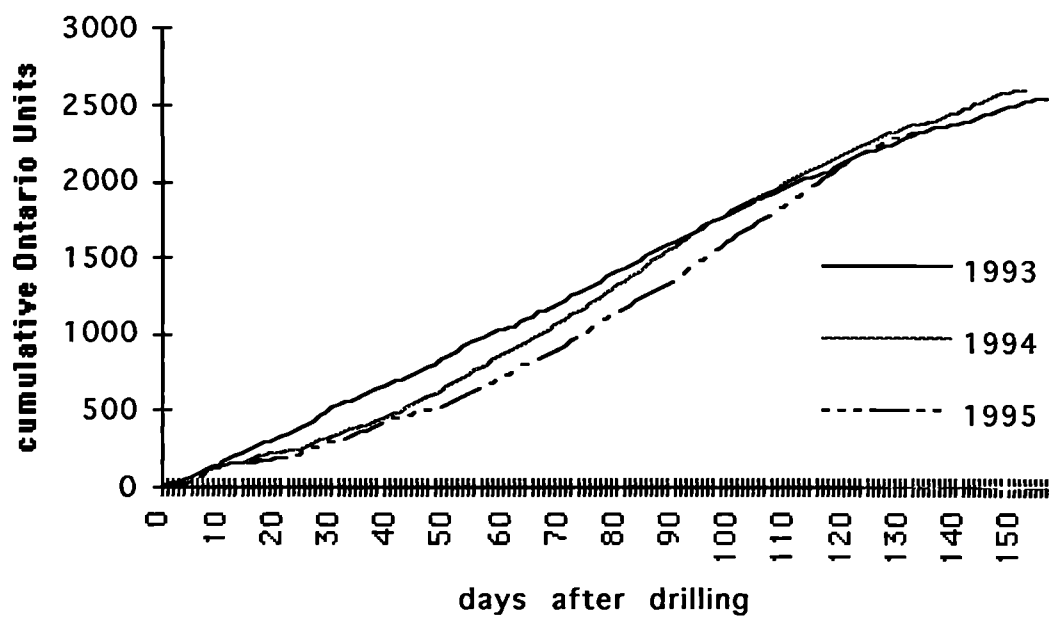


Figure 9.1 Cumulative Ontario Units from maize drilling in the 1993-1995 field experiments in Wye

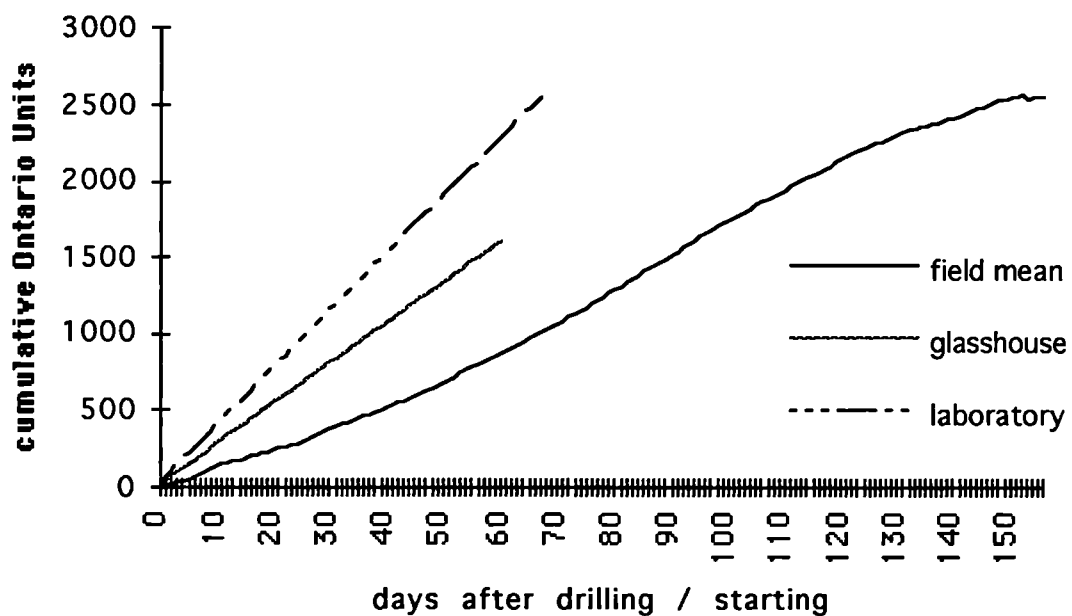


Figure 9.2 Cumulative Ontario Units in Wye from the start of the field and glasshouse (1993-1995 means) and the laboratory (1995/96) experiments

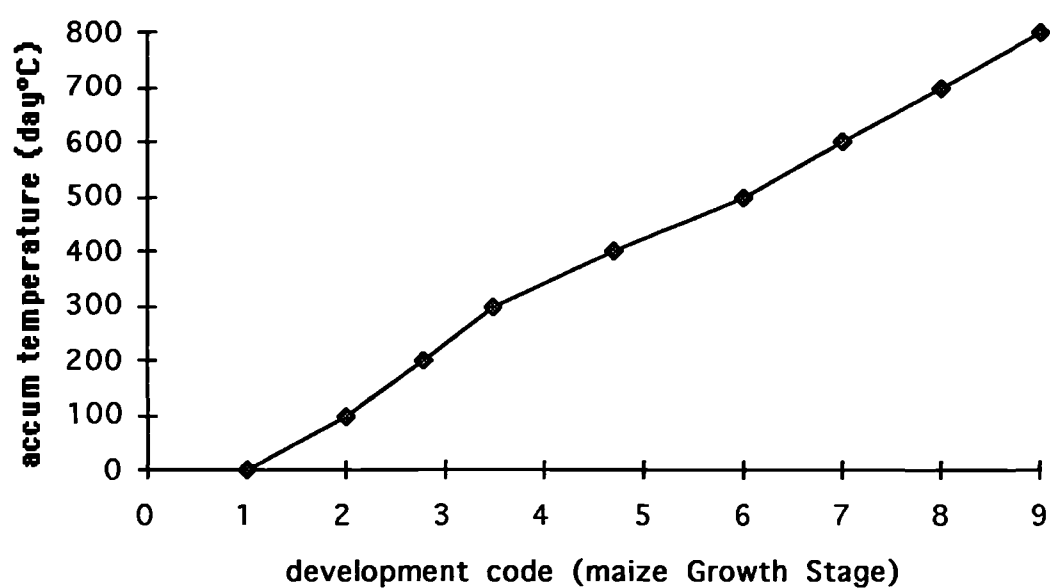


Figure 9.3 General relationship between maize growth stages (GS) and accumulated effective temperature (day°C; after Groot *et al* 1986)

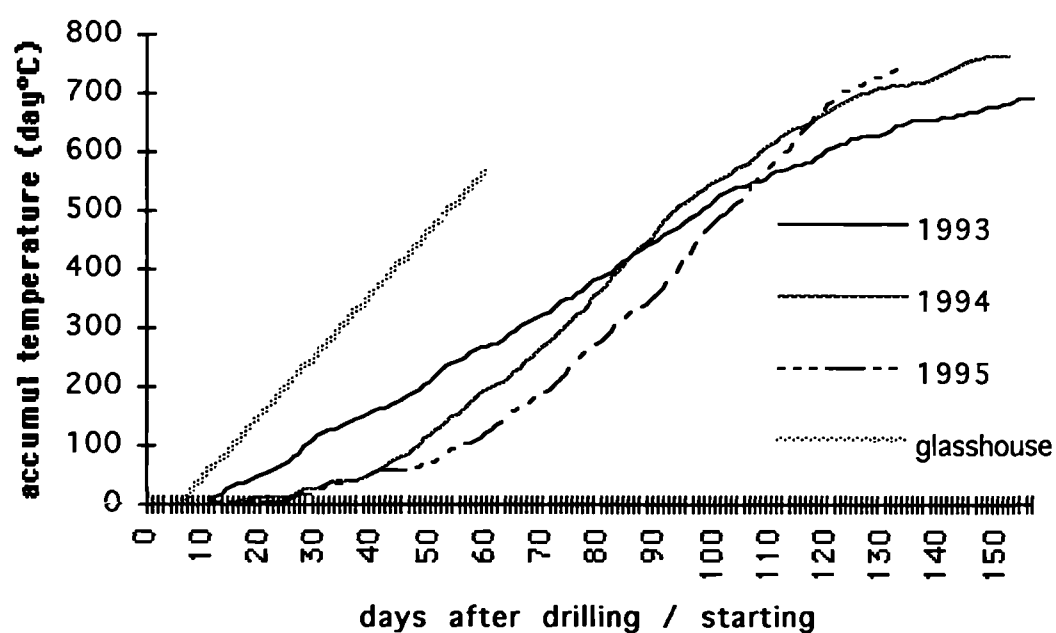


Figure 9.4 Accumulated temperature (day°C) from maize emergence in field (1993-1995) and glasshouse (1993-1995 mean) experiments in Wye

Under field conditions, OU accumulation was slower both in the beginning and at the end of the growing seasons, reflecting the lower temperatures at those periods. Accumulation of 1500 OU occurred at approximately 40 days after the experiment started in the laboratory, but took 55 days in the glasshouse and 90 days in the field.

9.3 Rainfall

9.3.1 Seasonal variations between field experiments

The water regime was controlled in the glasshouse and laboratory experiments, as described in Chapters 7 and 8, respectively.

Large variation occurred in the monthly total rainfall under field conditions during all growing seasons in Wye and in Viterbo (Table 9.2). Values for October 1995 are not shown, as maize was harvested in September that year, both in Wye and in Viterbo. Considering the total rainfall from April to September, the 1995 growing season in Wye was the driest, monthly totals being consistently lower than those from 1993 and 1994 in Wye, and from 1995 in Viterbo. The exceptions were in September, when the 1995 growing season in Wye was the wettest, and in July, that was particularly dry in Viterbo.

Table 9.2 Monthly total rainfall (mm) during the 1993-1995 field experiments in Wye and in Viterbo (1995 only)

month	Wye			Viterbo
	1993	1994	1995	1995
April	80.3	89.0	14.6	83.2
May	37.0	84.8	28.5	53.4
June	56.8	43.4	22.2	36.2
July	58.7	36.1	18.2	0.4
August	42.1	105.8	14.3	112.4
September	82.3	69.5	109.5	69.4
October	145.2	102.6	n/a	n/a
Total Apr-Sep	357.2	428.6	207.3	355.0

The total rainfall (Apr-Sep) in 1994 in Wye was the highest, August being the wettest month, with a large difference from the other growing seasons in Wye. The August totals were also the highest of all months in Viterbo in 1995, the dry conditions in July being followed by high rainfall.

9.4 Photoperiod

9.4.1 Comparisons between field, glasshouse, and laboratory conditions

Photoperiod (daylight length) was not relevant to the laboratory experiment. Field experiments in Wye and Viterbo were all conducted during practically the same months of the year, thus their photoperiod was very similar.

Glasshouse experiments were carried out at different periods of the year, as they were not dependent upon seasons. The 1994 experiments had the same photoperiod as in the field, since one was conducted during May and June, and the other from July to October. The 1995 experiment had also a similar photoperiod to the normal maize growing season, running from April to May. However, the 1993 glasshouse experiment had a shorter photoperiod than the others in the field and in the glasshouse, as it was carried out from February to April.

No additional lighting was used in the glasshouse, as maize etiolation did not occur. However, the glass reduced the photosynthetically active incoming radiation inside by between 20% (clear day) to 30% (overcast day), when compared to outdoor conditions (Chapter 3).

9.5 Discussion

Climatic conditions such as temperature and rainfall have a direct influence in maize productivity and in mineralisation rates of organic nutrients applied to soil (Bunting 1978; Ross *et al* 1995). Both crop growth and mineralisation rates are accelerated in warmer conditions, provided that the supply of water is adequate for maize development and for the microorganisms in soil.

The lower temperatures in Wye in 1994, at the beginning of the growing season, slowed maize growth at its early stages of development. However, that was compensated by increased temperatures at mid-season, the higher

heat unit accumulation causing a faster maize development, and resulting in adequate maize dry matter production by harvest (Chapter 5).

The period between July to September corresponds to a faster crop growth rate, which is often at its peak one or two weeks before flowering, remaining at a high level until early September (Bunting 1978). The monthly increments in shoot dry weight are approximately 2, 22, 46, 22 and 8% of the final total, respectively, from mid-June to mid-October, when the crop is usually harvested (Bunting 1978). The higher temperature from July to September in Wye, during the 1995 growing season, resulted in faster accumulation of heat units and of dry matter in maize, particularly in September. This was the cause for the early harvest, as maize had already reached a high dry matter content (> 30%) by then (Chapter 6).

The higher temperatures in Viterbo, as compared to all Wye growing seasons, probably increased crop growth rates and mineralisation conditions of organic nutrients on soil. The low rainfall in July in Viterbo, added to the very high temperatures at that month, probably resulted in water deficiency for maize. However, the high rainfall in August, with continued warm conditions, provided ideal conditions for mineralisation processes and maize biomass production at the period of its highest growth rate.

The 1995 growing season in Wye was considerably drier than the others, both in Wye and in Viterbo. The high rainfall in September 1995 in Wye was not of benefit to maize, as this was harvested by the beginning of that month. Accumulation of heat units started slowly, but increased during the period of faster maize growth, being adequate for maize development. The reduced levels of water available to the plant were probably the main reason for the reduced maize growth, resulting in lower overall yields as compared to the average maize production potential (Chapter 6).

Comparison of results from field, glasshouse and laboratory experiments would be inadequate if based on calendar time. Accumulation of heat units, and consequently maize growth, were much faster in the glasshouse than in field conditions. At two months in the glasshouse, the crop had reached the same stage of development as it would after one further month in the field. Thermal time and maize developmental stages are more appropriate for direct comparison between field and glasshouse results.

An even faster accumulation of heat units occurred in the laboratory, taking approximately 65 days to reach the 2500 OU required for full maize development, which occurs usually after 150 days in the field. Water levels at the laboratory experiment were optimum for mineralisation processes. Considering that availability of water in the field was also adequate, and that temperature is a key factor influencing mineralisation, the rates in the laboratory after nine weeks (65 days) would be approximately equivalent to those attained in the field during the whole maize growing season.

The shorter photoperiod during the 1993 glasshouse experiment probably resulted in reduced maize development and photosynthetic capacity, as both parameters are dependent on light availability.

Chapter 10. General Discussion and Conclusions

10.1 Introduction

This research project aimed to rationalise a sustainable production system for maize, with the use of dairy manure compost as an organic fertiliser. The effects of compost application on soil chemical and biological fertility (i.e. soil nutrients and microbial biomass and activity), on maize nutrition and on maize and weed growth were examined in field and glasshouse experiments (Chapters 4-7). Interactions between soil and plant were also observed (Figure 1.1, Chapter 1). A laboratory experiment (Chapter 8) was carried out to examine the rates of compost N mineralisation under controlled conditions.

A general discussion about the mineralisation rates of compost in field and glasshouse conditions based on the results of the laboratory experiment and taking into account the different climatic conditions (summarised in Chapter 9) is presented in this chapter. The effects of compost on soil fertility and maize production in all the experiments, together with the nutrient dynamics between compost and crop are also discussed. Recommendations for future research are presented and finally the conclusions from this research project are stated.

10.2 General Discussion

10.2.1 Mineralisation of compost nitrogen

Brinton (1985) and Brinton and Seekins (1994) suggested that 15-20% of compost N would mineralise during a maize growing season, based on maize N uptake under field conditions. Accordingly, a mineralisation rate of 20% was used in this research, to calculate the amount of compost applied in field and glasshouse experiments (Chapters 4-7). This aimed to ensure that both compost and Nitram applied were approximately equivalent in terms of N availability.

Multiple interactions between soil and compost can occur during mineralisation-immobilisation processes, and the mineralisation rate does

not change linearly with time. Results from the laboratory experiment (Chapter 8) supported previous work in that mineralisation is faster in sandy soils, or those with low organic matter content, than in clay soils, or those with high organic matter levels. The latter would retain more microbial biomass in the adsorptive clay particles, and its nitrogen compounds would resist degradation, because of complex substances being formed with humic materials (Sørensen 1975; Brown 1982; Rubaduka *et al* 1993).

Additionally, soil temperature and moisture levels play important roles in mineralisation processes. Given an adequate supply of water, mineralisation is faster in warmer conditions. Thus, when trying to relate the results obtained in the laboratory to the field and glasshouse conditions, the accumulation of heat units is more appropriate than is calendar time.

As reported in Chapter 9, 2500 Ontario Units (OU) are necessary for full maize development in England, taking approximately 150 days under field conditions in Wye, where experiments were conducted. In the laboratory conditions, only 65 days (approximately nine weeks) were necessary to reach the same required OU. Assuming that other conditions were similar, the rates of compost N mineralisation by week nine in the laboratory would then be approximately equivalent to those achieved under field conditions at the end of the maize growing season.

Results obtained in the laboratory experiment, using soil from the same area where the field experiments were conducted, showed that approximately 20% of the compost N was mineralised after nine weeks (UK soil; Figure 8.2, Chapter 8). It is important to note that this rate would vary depending on other factors (e.g. soil type, moisture levels). In the same laboratory experiment, approximately 35% of compost N was mineralised during the same period with a different soil type (from Brazil, sandy, with low organic matter content).

However, assuming that moisture levels were adequate for mineralisation processes, and that the compost used and the soil type were the same in both field and laboratory experiments, the rate of 20% suggested by Brinton (1985) and Brinton and Seekins (1994), and used as a basis in this research, seems appropriate for calculating the amount of compost that was applied in field experiments in Wye. The rate of 20% would, in theory, be achieved at

the end of the growing season, thus compost nitrogen was gradually made available to the crop in the field during its various development stages.

In the glasshouse, substrate moisture was usually kept adequate for maize development, and hence at levels approximately similar to those in the laboratory experiment. Using the cumulative Ontario Units as a guide (Figure 9.4, Chapter 9), the rates of mineralisation after 30 and 60 days in the glasshouse would be approximately equivalent to those after 20 and 40 days, respectively, under laboratory conditions. If the same UK soil was used in the glasshouse experiments, only approximately 7-14% of the compost N would have been mineralised after 30-60 days (the period in which the glasshouse experiments were conducted), respectively. However, peat compost (Chapter 3) was the substrate to which compost was applied, and its higher organic matter content may have delayed the mineralisation processes. Therefore, the availability of compost N in the glasshouse experiments was probably less than the 20% rate estimated, due to the slow mineralisation process at first, and to the short period in which glasshouse experiments were conducted. That would explain the lower N uptake by maize and its lower biomass production in compost- than in Nitram-treated pots in the 1994 A and the 1995 glasshouse experiments (Sections 7.2 and 7.4, respectively, Chapter 7).

10.2.2 Compost effects on soil fertility and crop production

This research compared the use of organic and inorganic fertilisers in maize production. In the 1993 field experiment (Chapter 4) composted and fresh dairy manure were used as organic fertilisers, the former showing higher maize dry matter yields than the latter. The fresh dairy manure applied had a high C/N ratio due to its high straw content, resulting in N immobilisation by the microorganisms (reflected in a larger microbial biomass). Thus, the lower N availability for the crop resulted in lower maize dry matter yields with fresh than with composted dairy manure. In manure-treated plots without weed control, competition for nutrients by weeds was added to that from microorganisms, and their synergistic effect resulted in even lower maize biomass production. Compost had a stable C/N ratio of approximately 10, very similar to that found in most agricultural soils, and its application did not result in N immobilisation, at least not in levels to significantly decrease maize yields. Based on this result, the application of

compost is preferable to fresh dairy manure, because the stable C/N ratio of the organic input would avoid the risk of N immobilisation.

Soil is a very complex system, and it is not easy to determine nutrient dynamics on it, as several factors interact at any given moment. However, some patterns could be identified in relation to nutrient movement from compost to crop in this research project, which were in agreement with previous works (e.g. Anderson and Domsch 1980; Jenkinson and Ladd 1981; Brussard *et al* 1993; Wardle *et al* 1993). When compost was applied to soil, available nutrients were taken both by microorganisms and by plants (crop and weeds). Simultaneously, organic nutrients from compost and from soil were gradually mineralised by the microorganisms, and then nutrients were either incorporated in their own living biomass or immediately made available to plants. Results from all three years of research demonstrated that compost increased both soil biological and chemical fertility. Despite the originally high soil organic matter in Wye (where most of the experiments were carried out), which would tend to mask treatment effects, soil with compost application still showed higher soil organic matter content and microbial biomass carbon (BC) and nitrogen (BN) than did soil with inorganic fertilisation. Microbial biomass acted as a storage and a source of nutrients to plants, as its decomposition provided readily available nutrients for the crop.

Higher levels of soil total N and extractable P, K and Mg were associated with compost application, tending to remain high at the end of the growing season in all field experiments. Potassium levels were particularly high in soil with compost addition, as dairy manure (the raw composting material; Chapter 3) is rich in this nutrient. Residual effects from compost application in the 1994 Field A experiment (Chapter 5) were observed, as total-N and extractable P, K and Mg levels were generally highest in compost-treated plots, before treatment application in the 1995 *Field 2 years* experiment (Chapter 6; a redrill of the 1994 Field A experiment). Additionally, cumulative effects of compost application were observed in the 1995 *Field 2 years* experiment, with increased levels of P, K and Mg after two years of compost addition. These patterns showed compost's potential for sustainable soil fertility, as nutrient levels were kept high to the following growing season, and as they increased with continued compost application.

In the 1993 field experiment (Chapter 4), although results from compost applied as a mulch were, in general, not significantly different from compost incorporated into soil, a greater mineralisation of compost nutrients in the latter was suggested by a tendency for soil nutrient levels to be higher in soils where compost was incorporated rather than applied as a mulch. Therefore, incorporation appeared to be preferable to mulching, in the conditions of the field experiments in this research. However, under drought conditions, application of a mulch might be preferable, to avoid soil water losses from evaporation (Lal 1974; Wardle *et al* 1993). It is important to note that soils with compost application, either incorporated or as a mulch, had a consistently higher availability of water than those with Nitram application in all Wye field experiments, probably as a result of the higher organic matter content of compost-treated soil. As well as increasing the pool of microbial biomass, compost also increased soil organic matter content with its more complex and slowly decomposed molecules such as lignin and cellulose, that were bound to be stored in soil organic matter, thus contributing to enhance soil physical properties such as water retention. When comparing compost and Nitram effects under drought conditions (in the 1995 glasshouse experiment, Section 7.4, Chapter 7), the former resulted in higher maize fresh biomass yields. Thus, compost application would be especially preferable to inorganic fertilisers in dry areas, not only as a nutrient supplier, but also because of the additional effect of increasing the availability of water to plants.

In field experiments, soil nitrate levels generally showed a negative relationship with soil total-N and BN levels, being lower with compost than with Nitram application. Nitrate levels remained low in compost-treated soil even at higher rates of application or with repeated compost addition, indicating a slow and gradual mineralisation of compost N. In contrast, soil nitrate content increased with higher rates of Nitram fertilisation, showing even higher values after two consecutive applications. Maize uptake of N is minimal during initial stages of crop development, and increases gradually to a maximum between flowering and early grain formation (Pain 1978; Fageria *et al* 1991). The higher soil nitrate levels at the beginning and at the end of crop growth stages, the greater its leaching and, thus, polluting potential (Magdoff 1991; Maynard 1993). Therefore, compost consistently showed lower pollution potential than did Nitram in this research project.

The higher nitrate content in soils with Nitram application tended to be more beneficial for weeds than for maize and for microorganisms. Despite the high levels of available nitrogen in Nitram plots, its BN levels were generally lower than in compost plots, suggesting that the use of nitrate by microorganisms was limited. In general, no significant differences occurred in maize dry matter yields between Nitram- and compost-treated plots with weed control in field experiments. It showed that, although mineralised N from compost was at lower levels than the readily available N supplied by Nitram, it was, without weed competition, still adequate for maize development. Weeds competed strongly with the crop for resources, and they immediately benefited from available nutrients in soil. In the presence of weeds, results from Wye indicated that the excess of nitrate reduced the competition for nitrogen between crop and weeds, as maize biomass production tended to be higher in Nitram- than in compost-treated plots. However, despite greater weed competition, no such differences were found with two years of application of compost (1995 *Field 2 years* experiment, Chapter 6), suggesting that compost N mineralisation would increase once the soil ecosystem had adjusted to a new equilibrium with organic inputs (Doran *et al* 1987). In Viterbo, with only one year of application, maize biomass production was higher in compost- than in Nitram-treated plots in the presence of weeds (Chapter 6). Although this difference was not significant, it still showed that the climatic conditions allowed faster mineralisation of compost N in Viterbo and enabled an adequate supply of available N for maize, even when there was strong weed competition. In contrast, weed biomass production and its uptake of nitrogen showed, in general, a positive correlation with soil nitrate levels, indicating that weeds promptly benefited from the excess of available nitrogen.

Weed competition was very detrimental to maize development and to the feeding quality of forage in all field experiments. Crop biomass production was consistently lower in plots without weed control. A lower percentage of cob in maize dry matter production in the presence of weeds reduced the quality of the forage, as the cob is the more digestible part of the maize plant. Additionally, the presence of weeds in maize rows, and thus in the harvested material, resulted in a lower digestibility of the forage. As indicated by the 1994 B glasshouse experiment (Section 7.3, Chapter 7), mature compost had no potential itself for weed infestation, because any weed seeds present in the raw material (dairy manure, weeds mixed with the straw) would be killed during the composting process (Kiehl 1985; Ott

1990; Dalzell *et al* 1987). This would be a further advantage of using composted instead of fresh dairy manure. However, although not contributing to increased weed infestation, compost showed no effect in controlling it when applied as a mulch (1993 field experiment, Chapter 4), contrary to suggestions of previous workers (Titov and Babakov 1988; Schmalzle 1990; Lee *et al* 1992; Ligneau and Watt 1995). Higher rates of application might provide some physical control on weed emergence, but then the economical viability and the chemical and biological effects of such rates on soil and maize would need to be considered. It is clear that weed control is necessary for adequate maize dry matter yields, and in a sustainable system an alternative to herbicide application would be necessary, but its study was not the objective of this research.

In contrast to maize, at least in the short-term, microorganisms were apparently not affected either by weed presence or by herbicide application, as there were in general no significant differences in biomass or activity between plots with or without weed control. This indicated a higher competitiveness for nutrients by microorganisms than by maize plants in the presence of weeds. During periods of lower nutrient uptake by the crop, microbial biomass increased, as microorganisms benefited from the nutrients available, even in the presence of weeds. However, during the period of maximum maize uptake of nutrients, particularly N, not only did soil nutrient levels decrease, but so did the size of soil microbial biomass in all field experiments. The increased microbial activity during the same period indicated the greater competition for nutrients. Higher microbial activity results in greater nutrient mineralisation, but can also denote microbial inefficiency, as a higher respiration rate per unit of biomass occurs in conditions of ecological disturbance or lower availability of resources, such as nutrients (Visser and Parkinson 1992; Wardle *et al* 1993). Microbial activity tended to be higher in Viterbo than in Wye, as the warmer conditions of the former accelerated microbial biomass turnover, and nutrient availability to microorganisms was limited due to the lower organic matter content in soil. Thus, microbial biomass decomposition provided further nutrients to plants during the period of higher crop demand. At the end of the growing season, plant competition for nutrients ceased, and the fresh substrate then available, in the form of decomposing shoot and root material, contributed to an increase in microbial biomass, particularly in soil with compost application. The larger the size of microbial biomass, the more sustained is soil fertility, as nutrients are kept in the biomass for the next growing season.

Carbon is a limiting factor in microbial biomass production, and its supply by compost, along with other nutrients, was probably the reason for the higher BC and BN levels in compost-treated soils, even at the peak of plant competition for nutrients (maize flowering) in both Wye and Viterbo field experiments. The lower microbial activity in soils with compost than with Nitram application during the same period further indicated the greater availability of nutrients in these plots. Microorganisms apparently make a more efficient use of organic N than plants, as indicated by the higher BN levels in soils with compost application, with a lower nitrate content than those with Nitram application. Microorganisms are both a source and a sink of nutrients in soil, being the most available source of plant nutrients after mineralisation. Thus, the higher microbial biomass in soils with compost application indicates the potential of compost to sustain soil fertility.

The higher level of nitrate available in soils with Nitram application resulted in higher N uptake by maize and weeds. In field experiments with weed control, differences in N uptake were not reflected in differences in maize biomass yields, as the amount of compost N mineralised during the growing season appeared to be adequate for maize development. However, in the 1993 and 1995 glasshouse experiments (Sections 7.1 and 7.4, respectively, Chapter 7), maize dry matter yields tended to be lower with compost than with Nitram application, although this difference was not significant in the latter experiment. Nitram-N was in readily available form, whereas the mineralisation of compost N occurred gradually. As indicated by the laboratory experiment results (Chapter 8 and Section 10.2.1), mineralisation of compost N would start slowly in substrates with high organic matter content, such as those used in glasshouse experiments. During the short period in which these experiments were carried out, the amount of compost N mineralised was probably not sufficient for adequate maize development, hence the lower dry matter yields with compost than with Nitram addition.

In contrast, potassium availability was higher in soils with compost application, resulting in higher K uptake by the maize plant. This 'luxury' consumption of K resulted in low Ca and Mg uptake by maize with compost application, despite the higher levels of these nutrients on soil with compost addition. That occurs because the plant absorbs K^+ ions in preference to Ca^{++} and Mg^{++} ions, and as the sum of K, Ca and Mg individual percentages in plant tissue is generally constant at all stages of development, a higher percentage of K will cause a lower percentage of Ca and Mg

(Tisdale and Nelson 1975; Pain 1978; Marschner 1986). These results for maize K, Ca and Mg uptake were observed in both field and glasshouse experiments in Wye. Uptake of phosphorus by maize was also higher under compost application in the glasshouse conditions, but not in the field, although higher levels of P were found in soil. The high soil organic matter probably contributed to masking the effects of compost on P uptake by maize in the field. Uptakes of P, K, Ca and Mg by weeds were generally higher in plots with Nitram than with compost application, because of the higher weed biomass production with the former. Thus, higher nutrient uptake occurred with Nitram, despite the higher concentration of these nutrients in weed tissue with compost application (data on nutrient concentration not presented). In the case of weed N uptake, both N concentration in weed tissue and weed biomass production tended to be higher with Nitram application.

The higher K percentage in maize plants with compost application could be the reason for their lower dry matter content and their higher fresh biomass production and leaf area index (LAI) in the first field experiment (1993, Chapter 4). Potassium plays an important role in water regulation in plants, increasing water uptake and reducing its loss. The water regime of higher plants is controlled by stomatal movements, which are directly regulated by potassium. This nutrient is also the predominant osmotic solute in the vacuole, being able to maintain a high water content in plant even under drought conditions (Marschner 1986; Mengel and Kirkby 1987). The higher soil water content associated with compost addition could also be the reason for the higher fresh biomass yields, because of the higher availability of water to plants (Metzger and Yaron 1987). Another factor contributing to the delay in maize maturity could be the higher absorption of nutrients by plants caused by a direct action of humic molecules. Passive membrane permeability to protons can be increased by the low molecular weight humic molecules of compost, thus increasing plant capacity to absorb nutrients over a longer period of time (Varanini *et al* 1993). This process would effectively delay plant maturity.

Thus, results from the 1993 field experiment suggested a potential for higher productivity of maize under compost application, as the higher fresh biomass production could result in higher dry matter production if there was adequate time for the plant to increase its dry matter content towards maturity. Accumulation of the necessary heat units occurred relatively late

in the 1993 growing season (Chapter 9), and maize was harvested at a comparative low DM content. To investigate the potential for higher productivity, the cultivar used in that field experiment (*LG2080*) was compared with *Aziz*, an earlier maturing one (1994 Field B experiment, Chapter 5). However, *Aziz* proved an unsuitable cultivar for examining compost effects, as it responded better to chemical fertiliser. Despite reaching maturity with high DM content, maize cultivar *Aziz* showed higher nutrient uptake and biomass yields with Nitram than with compost application, the opposite to what was expected, and to what occurred with maize cultivar *LG2080*. This was probably because cultivar *Aziz* had been selected for high input agriculture, benefiting from high levels of readily available nitrogen to increase its dry matter production. It was concluded that the use of another earlier maturing cultivar selected for low-input agriculture might show a correlation between delay in maturity and the higher potential for crop productivity under compost application.

When examining the results of the 1995 field experiments in Wye, with cultivar *LG2080* under faster accumulation of heat units, maize DM content at harvest was again higher with Nitram than with compost application, but no significant differences were found in either fresh or dry matter yields. Results from the experiment conducted in Viterbo, Italy, with warmer temperatures and faster crop growth rates than in Wye, showed no significant differences neither in DM content nor in maize biomass production. Thus, an apparent delay in maturity occurred in compost-treated maize in temperate but not in Mediterranean conditions. In Wye, the faster accumulation of heat units in 1995 resulted in a faster crop development compared to the previous field experiments. However, even though there was adequate time for maize to reach its full potential of dry matter production, as indicated by the high levels of DM content, this did not result in higher dry matter production with compost application either in Wye or in Viterbo. A correlation between delayed maturity and potentially higher productivity of maize under compost application was not found. From the results of all field experiments, it seems that the lower dry matter content of compost-treated maize in Wye may be also associated with the lower availability of N in compost-treated soil. Nitrogen is essential for plant growth because it is a constituent of all proteins, thus a lower supply of N results in a lower accumulation of dry matter. The maize plant still had higher fresh biomass yields with compost application in the 1993 and 1994 Wye growing seasons. That could be associated with a higher water content

in the plant due to the reasons previously discussed (higher K percentage in plant tissue, higher water availability in soil, higher membrane passive permeability). In Viterbo, the faster mineralisation rates of compost N ensured that maize dry matter production was at the same levels as that with Nitram application, thus no differences between fertilisers were found in maize DM and biomass production. The accelerated heat unit accumulation and the lower water availability in the 1995 growing season in Wye, compared to the previous years, may have contributed to the lack of significant differences in maize fresh biomass yields that year.

It is important to note that, even with adequate nutrient supply, maize dry matter yield potential can be reduced because of other factors, some of which occurred during this research project: the shorter photoperiod in the 1993 glasshouse experiment (Section 7.1, Chapter 7) probably contributed to the low overall biomass production (not considering differences due to treatments), because the experiment was conducted during late winter-early spring; initial weed competition greatly retarded maize development in the 1994 Field A experiment, resulting in lower overall yields; and the water shortage during the 1995 field experiments in Wye, due to low rainfall, was probably related to the lower than average dry matter yields. Temperature also plays an important role in maize development, with accumulation of dry matter, and hence yield potential, increasing in warmer conditions.

Despite the lower supply of nitrogen in conditions of slower mineralisation, the lack of significant differences in maize dry matter yields between Nitram and compost application clearly indicated the potential of the latter as a fertiliser in a sustainable maize production. During the transition period from inorganic to organic fertilisers, short-term yield losses can occur as the soil system reaches an equilibrium with increased microbial biomass (Doran *et al* 1987, Fauci and Dick 1994a). The levels of N supplied, although lower than those achieved with Nitram fertiliser, were nonetheless adequate for maize production, with a much lower potential for pollution of the ground water table. With warmer temperatures and faster mineralisation processes, such as in Viterbo, maize supply of nitrogen by compost was adequate even in conditions of weed competition. Moreover, maize N supply tended to increase in Wye conditions with consecutive application of compost (1995 *Field 2 years*, Chapter 6), probably due to the increased size of microbial biomass, once soil ecosystem had adapted to organic inputs. Through

mineralisation processes, the increase in N supply could result in increased maize dry matter yields over a longer term.

10.3 Recommendations for Future Research

This research project found evidence of the ability of compost to increase and maintain soil fertility in the short-term, over one and two years of application. However, long-term experiments are needed to further examine its effects on sustaining soil fertility. The potential for increased crop yields under compost application over a longer period should be investigated.

Continued studies of compost application on areas with lower native soil organic matter content would enable a better understanding of compost effects on soil chemical, physical and biological properties.

Subsequent studies on mineralisation of compost nutrients should be made, under controlled and uncontrolled conditions, to allow more accurate estimation of the rates of application for adequate crop fertility.

Cultivars adapted to organic or low input agriculture are needed, so that the crop's full production potential can be achieved under organic fertilisation.

Research on weed control methods needs to be developed, to find less environmentally damaging alternatives to herbicides which are effective in reducing weed competition.

Economic aspects of substituting chemical fertilisers for compost in crop production should be thoroughly investigated, taking into account not only the value of compost as a nutrient supplier, but its capacity to enhance soil biological, chemical and physical properties in a sustainable way.

10.4 Summary and Conclusions

1) Composted dairy manure can supply maize's nutrient requirements, with crop dry matter yields equivalent to those attained under mineral fertilisation, provided that mineralisation conditions are adequate.

2) Soil chemical and biological fertility are enhanced by application of composted dairy manure, with increased microbial biomass production and higher levels of soil nutrients, such as total-N and extractable P, K and Mg. As the microbial biomass stores nutrients, which are gradually made available to plant through mineralisation processes, its size is directly related to soil fertility, i.e. the larger the microbial biomass pool, the more fertile is the soil over a period of time. Thus, compost application can potentially sustain soil productive capacity, by increasing microbial biomass production and soil nutrient levels.

3) The lower potential of compost for nitrate pollution was demonstrated by the lower levels of available nitrogen in soil treated with compost, even at higher rates or with repeated application. Nitrate levels were high in soil treated with Nitram, showing a positive relationship with the rate of application, further increasing with consecutive inorganic fertilisation.

4) There was strong evidence that maize under drought conditions would have higher dry matter yields with compost than with inorganic fertiliser application, because of the effect of compost in increasing soil water holding capacity.

5) When comparing composted and fresh dairy manure, the former was preferable as a fertiliser due to its stable C/N ratio, thus avoiding risks of nitrogen immobilisation, which could reduce maize dry matter yields. Moreover, unlike fresh manure, compost showed no potential for weed infestation, as weed seeds were killed during the composting process.

6) Weed competition strongly decreased maize dry matter yields and the feeding quality of the forage, thus emphasising the need for adequate weed control in maize production. Compost application, either incorporated or applied as a mulch, had no significant effect in controlling weeds, but lower levels of weed infestation were generally associated with compost than with inorganic nitrogen use.

7) In this research project, no evidence was found of either weed competition or herbicide application having any negative effect on microorganisms. However, intense competition occurred during the period of higher nutrient demand by maize, causing a decrease in the size of microbial biomass and an increase in its activity. This denoted both nutritional deficiency for

microorganisms and increased nutrient availability to maize, through mineralisation processes.

8) The supply of compost nutrients to maize was higher under conditions of faster mineralisation, as higher temperatures, accelerating microbial biomass turnover and ensuring higher dry matter yields. Under sub-optimal mineralisation conditions, such as lower temperatures or a short growing season, compost supply of plant available nutrients is not sufficient to ensure adequate dry matter yields. There was evidence that the nutrient supply increased with repeated application of compost, probably because the soil ecosystem had adjusted to the new equilibrium with organic inputs, thus benefiting mineralisation processes.

9) It is not easy to estimate mineralisation rates of compost, as they vary depending on soil type, temperature and moisture levels, as well as on interactions between compost, soil and plant. Further research is necessary to better understand compost mineralisation processes.

10) A lower dry matter content in maize plants receiving compost was observed in some experiments, suggesting a delay in plant maturity. The higher water content could be caused by the higher potassium percentage in compost-treated maize tissue, the higher water availability in compost-treated soil, and/or the higher passive membrane permeability associated with compost use, reported in literature. This lower plant dry matter content could be also related to its lower N uptake, as differences in DM did not happen in faster mineralisation conditions.

11) There was evidence in this research for increased maize dry matter yields with repeated application of compost. This suggests a potential for higher crop biomass production with long-term compost application, which should be investigated.

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Appendix 1. Decimal code for maize developmental stages (Groot *et al* 1986)

<i>0</i>	<i>Germination</i>	<i>5</i>	<i>Flowering</i>
0.00	dry seed	5.00	start of pollen shedding
0.25	imbibition of the seed	5.25	50% pollen shedding
0.50	radicle emerged from seed	5.50	50% silking
0.75	coleoptile emerged from seed	5.75	end of flowering
<i>1</i>	<i>Emergence and Seedling Growth</i>	<i>6</i>	<i>Water Ripe (caryopsis)</i>
1.00	coleoptile emerging from soil	6.00	early water ripe, start of silk drying
1.25	first leaf unfolded	6.25	-
1.50	2 leaves unfolded	6.50	medium water ripe
1.75	3 leaves unfolded	6.75	late water ripe
<i>2</i>	<i>Stem Elongation (1)</i>	<i>7</i>	<i>Milk Ripe (MR)</i>
2.00	4 leaves unfolded	7.00	early milk ripe, silks entirely dry
2.25	5 leaves unfolded	7.25	first dents become visible
2.50	6 leaves unfolded	7.50	half MR, milk line halfway kernel
2.75	7 leaves unfolded	7.75	late milk ripe
<i>3</i>	<i>Stem Elongation (2)</i>	<i>8</i>	<i>Dry Ripe (DR)</i>
3.00	8 leaves unfolded	8.00	early DR, physiological maturity ‡
3.25	9 leaves unfolded	8.25	-
3.50	10 leaves unfolded	8.50	medium dry
3.75	11 leaves unfolded	8.75	late dry
<i>4</i>	<i>Stem Elongation (3) and Tasseling</i>	<i>9</i>	<i>Ripeness</i>
4.00	12 leaves unfolded	9.00	hard ripe
4.25	13 leaves unfolded	9.25	-
4.50	14 leaves unfolded	9.50	-
4.75	15 or more leaves unfolded	9.75	end of innate seed dormancy

‡ forage maize harvest

Appendix 2. Results of soil analysis prior to treatment application

Initial analysis of soil from *Orchard Field*, UK, for each experiment

Experiment - Year	pH	OM %	Total N %	P	K extractable (mg.litre ⁻¹)	Ca	Mg
Field - 1993 (Chapter 4) [‡]	7.9	4.6	0.22	35	163	3470	48
Field A - 1994 (Chapter 5)	8.0	4.5	0.16	51	63	1484	14
Field B - 1994 (Chapter 5)	8.0	4.8	0.16	61	122	1354	16
<i>Field 1 year</i> - 1995 (Chapter 6) [¥]	8.0	4.3	0.19	28	164	1620	48
Glasshouse - 1995 (Chapter 7)	8.2	4.0	0.18	26	145	1563	43
Laboratory - 1995/96 (Chapter 8)	8.0	4.5	0.16	32	133	1810	35

[‡] Analysis carried out by ADAS Wolverhampton

[¥] 1995 *Field 2 years* was a re-drill of 1994 Field A, hence individual soil analysis per plot were carried out and are presented in Chapter 6.

Initial analysis of soil from the *Cerrado* region, Brazil[‡]

Experiment - Year	pH	OM %	Total N %	P	K extractable (Cmol (+).litre ⁻¹)	Ca	Mg
Laboratory - 1995/96 (Chapter 8)	5.2	1.5	0.10	0.01	0.07	0.9	0.6

[‡] Analysis was carried out by EMBRAPA, Brazil, and results are expressed in the units given (Miranda 1994).

Appendix 3. Analyses of dairy manure compost, fresh dairy manure and peat compost prior to application in experiments

All analyses reported here were carried out by ADAS Wolverhampton.

Analyses of dairy manure compost (DMC) and peat compost (PC) used in 1993 Glasshouse experiment

Type	pH	NO ₃ -N	NH ₄ -N	Ext P	Ext K	Ext Ca	Ext Mg	conductivity
mg.litre ⁻¹								µS
DMC	8.1	283	4	240	4450	51	44	2470
PC	6.1	10	14	3	26	57	10	98
	density g.ml ⁻¹	DM	total N	total P	total K	total Ca	total Mg	organic C
% DM								
DMC	0.63	64	-	-	-	-	-	-
PC	0.60	56	-	-	-	-	-	-

Analyses of dairy manure compost (DMC) and fresh manure (FM) used in 1993 Field experiment

Type	pH	NO ₃ -N	NH ₄ -N	Ext P	Ext K	Ext Ca	Ext Mg	conductivity
mg.litre ⁻¹								µS
DMC	7.7	-	0.01%	-	-	-	-	-
FM	8.6	1	803	326	3180	85	87	196
	density g.ml ⁻¹	DM	total N	total P	total K	total Ca	total Mg	organic C
% DM								
DMC	0.59	31	2.48	1.10	2.40	4.26	0.86	25.2
FM	-	31	2.88	0.40	3.14	2.14	0.26	85.2

Analyses of dairy manure compost (DMC) and peat compost (PC) used in 1994 Glasshouse experiments

Type	pH	NO ₃ -N	NH ₄ -N	Ext P	Ext K	Ext Ca	Ext Mg	conductivity
mg.litre ⁻¹								µS
DMC	7.8	167	3	149	1380	30	20	893
PC	6.1	8	13	4	21	56	7	88
	density g.ml ⁻¹	DM	total N	total P	total K	total Ca	total Mg	organic C
% DM								
DMC	0.54	50	2.31	1.00	1.14	5.06	0.40	24.1
PC	0.52	51	0.24	0.01	0.02	0.35	0.04	9.8

Analyses of dairy manure compost (DMC) used in 1994 Field experiments (A and B)

Type	pH	NO ₃ -N	NH ₄ -N	Ext P	Ext K	Ext Ca	Ext Mg	conductivity
				mg.litre ⁻¹				µS
DMC	8.7	11.2	1	248	2680	83	34	1670
	density	DM	total N	total P	total K	total Ca	total Mg	organic C
	g.ml ⁻¹			% DM				
DMC	0.57	29	2.79	1.13	3.06	2.74	0.46	27.5

Analyses of dairy manure compost (DMC) used in 1995 Glasshouse experiment, 1995 Field experiments (*Field 1 year* and *2 years*, Wye) and 1995/96 Laboratory experiment

Type	pH	NO ₃ -N	NH ₄ -N	Ext P	Ext K	Ext Ca	Ext Mg	conductivity
				mg.litre ⁻¹				µS
DMC	8.7	24	96	527	10400	8060	133	1620
	density	DM	total N	total P	total K	total Ca	total Mg	organic C
	g.ml ⁻¹			% DM				
DMC	0.71	35	2.78	0.77	4.23	3.44	0.57	28.0

Appendix 4. Methods of soil chemical analyses

Total Nitrogen(Kjeldahl)

Digestion

Weigh 1 g dried, sieved (2 mm-mesh) soil into boiling tube. Add 5 ml H₂O, one catalyst tablet (1.5 g K₂SO₄ + 0.0075 g Se) and 4 ml conc. H₂SO₄. Place tube in aluminium block heater set at 200°C for 2 h. Increase temperature to 350°C for 4 h to complete digestion. Allow tube to cool. Add water, mix, make up to 100 ml and mix thoroughly. Carry out blank determination.

Determination of total N

Reagents-as recommended by the Burkard SFA2 auto-analyser manufacturer:

1. Buffer solution: 50 g potassium sodium tartrate + 14.2 g anhydrous disodium hydrogen phosphate + 54 g sodium hydroxide. Dissolve in 2 litre water and add 2 ml Brij 35.
2. Salicylate/nitroprusside: 0.4 g sodium nitroprusside + 34 g sodium salicylate. Dissolve in 1 litre water and add 1 ml Brij 35.
3. Sodium hypochlorite (10-14% available chlorine). Dilute 15 ml to 500 ml with water.

Method

Colour development determined with auto-analyser set to read absorbance at 660 nm, compared with standards.

Ammonium- and Nitrate-N, extractable, in moist soil

Extraction

Transfer 10 g moist fresh soil (sieved 5.6 mm-mesh) into 250 ml wide mouth bottle. Add 50 ml 2 M KCl, cap bottle, shake for 2 h on shaking machine (275 strokes per min, length of travel 25 mm). Filter through 150 mm Whatman No. 40 filter paper, retain filtrate for determination of NH₄⁻, NO₃⁻ and NO₂⁻ N. Carry out blank determination.

Determination of ammonium

Same method as for determination of total N.

Determination of nitrate and nitrite

Reagents

1. Reducing solution: 0.11 g hydrazine sulphate + 12.5 ml 20% sodium hydroxide + 1 ml 0.19% cupric sulphate (5 hydrate). Mix, make up to 250 ml with water.
2. Colour reagent: 5 g sulphanilamide + 0.25 g NNED (N-1-naphthylethylenediamine dihydrochloride). Add to 400 ml water, mix. Add 50 ml o-phosphoric acid, mix well. Make up to 500 ml.

Method

Nitrate and nitrite levels determined using auto-analyser set to measure absorbance at 540 nm. Both levels measured, then nitrite level subtracted from nitrate figure for true nitrate value.

Phosphorus, extractable

Extraction

Reagents

1. Polyacrylamide solution, 0.05% m/V: dissolve 0.1 g polyacrylamide in approx. 120 ml water, dilute to 200 ml.
2. Sodium bicarbonate reagent: dissolve 210 g sodium hydrogen carbonate in water, add 25 ml polyacrylamide solution, dilute to 5 litre. Add approx. 50% m/m NaOH solution until pH=8.50 at 20°C.

Method

Transfer 5 ml air-dried sieved (2 mm-mesh) soil into wide mouth bottle. Add 100 ml sodium bicarbonate reagent. Cap bottle, shake on shaking machine for 30 min at 20°C. Filter through 125 mm Whatman No. 2 filter paper, retain filtrate for phosphate determination. Carry out blank determination.

Determination of phosphate (Molybdenum Blue Method)

Reagents

1. Standards: from 1000 ppm P stock solution (4.393 g dry KH_2PO_4 in 1 litre) prepare working standards of 1, 2, 5, 10, 15, 20 ppm.
2. Ammonium molybdate-sulphuric acid reagent: dissolve in 40 ml warm water 5 g $(\text{NH}_4)_6\text{Mo}_7\text{O}_{24} \cdot 4\text{H}_2\text{O}$. Add 140 ml conc. H_2SO_4 to 200 ml water. Add molybdate solution to 130 ml diluted acid, make up to 200 ml.
3. Stannous chloride reagent: dissolve 0.1g $\text{SnCl}_2 \cdot 2\text{H}_2\text{O}$ in 50 ml 2% v/v HCl.

Method

Transfer 120 μl standard or sample into 3 ml polythene cuvette. Add 2.5 ml water, 120 μl ammonium molybdate reagent, 120 μl stannous chloride reagent and mix thoroughly. Leave for 30 min. Absorbance measured at 700 nm at NOVASPEC spectrophotometer.

Potassium and Magnesium, extractable

Extraction

Transfer 10 ml air-dried sieved (2 mm-mesh) soil into wide mouth bottle. Add 50 ml M ammonium nitrate, cap bottle and shake for 30 min. Filter through 125 mm Whatman No. 2 filter paper and retain the filtrate for K and Mg determination. Carry out blank determination.

Determination of potassium and magnesium

Potassium determined with flame photometer (Corning 410). Dilute filtrate 1:5 with LaCl_3 , and Mg determined with flame atomic spectrophotometer (Pye Unicam SP9).

Cation Exchange Capacity (CEC) and Exchangeable Cations (Calcium)

Extraction

Reagents

1. 1 M ammonium acetate, pH 7.0: measure 100-150 ml water into a 5 litre beaker. Add 288 ml glacial acetic acid and 300 ml 0.88 ammonia solution. Mix well, make up to 5 litre, check pH.

2. Ethanol (rectified spirit)

3. Potassium chloride 10% m/v, pH 2.5: 100 g KCl in 1 litre water, check pH.

Method

Transfer 5 g air-dried sieved (0.5 mm-mesh) soil into a 50 ml borosilicate glass beaker. Add 20 ml M ammonium acetate, stir, allow to stand overnight. Transfer contents of beaker into Buchner funnel fitted with 125 mm Whatman No. 44 filter paper, collect filtrate in 250 ml volumetric flask. Leach soil with successive 25 ml volumes M ammonium acetate, allowing funnel to drain between each addition, until nearly 250 ml filtrate collected. Dilute to 250 ml with M ammonium acetate, retain this solution (A) for Ca determination. Wash interior of funnel, soil and filter paper with five 25 ml volumes ethanol, allow funnel to drain between washings, discard washings. Leach ethanol-washed soil on filter paper with successive 25 ml volumes KCl solution, allow funnel to drain between each addition. Collect extracts in 100 ml volumetric flask, until nearly 100 ml collected. Dilute to 100 ml with KCl solution and retain this solution (B) for CEC determination. Carry out blank determination.

Determination of CEC

Cation exchange capacity determined from solution B using auto-analyser for ammonium-N determination.

Determination of calcium

Solution A diluted (1:5) with LaCl_3 (releasing agent) and Ca determined with flame atomic spectrophotometer (Pye Unicam SP9).

Moisture Content (Dry Matter Content)

Method

Weigh 10 g well mixed soil into dry-matter tin, place it with lid off in oven at 105°C for at least 24 hours. Cool tins in desiccator and re-weigh. Moisture and oven-dry soil percentages calculated from loss in weight.

Organic Matter Content

Determination of organic matter by loss-on-ignition

Weigh pre-ignited porcelain crucibles (A), add 5 g oven-dry soil, re-weigh (B). Ignite crucibles with samples in muffle furnace at 375°C for 16 h, allow to cool in desiccator, re-weigh (C).

% loss-on-ignition = $[(B - C)/(B - A)] \times 100$.

Soil pH

Method

Dispense 10 ml scoop soil into 60 ml polythene bottle, add 25 ml de-ionised water. Cap bottle and shake for 15 min. Measure pH in a pH meter calibrated with pH 4.0 and 7.0 buffer solutions. Wash electrode between samples and allow to stabilise in each sample for 1 min.

Appendix 5. Methods of analyses of plant material

Nutrient Analysis

Digestion of Plant Material

Used for N, P, K, Ca and Mg determination .

Mixed digestion reagent

In a fume cupboard, add 350 ml hydrogen peroxide (100 vol.) to 0.42 g selenium (powder) and 14 g lithium sulphate (monohydrate) in a 2 litre beaker. Carefully add 420 ml conc. H_2SO_4 , stirring slowly and cooling.

Method

Weigh 0.2 g dried ground (1 mm-mesh) sample into long boiling tube. Add 4.4 ml digestion reagent. Place tubes in block heater set at 150°C for 2 h, increase temperature to 350°C for a further 4 h until digest is clear. Allow tubes to cool, make digest up to 75 ml with de-ionised water. Run several blank digests to make up standards.

Determination of N, P, K, Ca and Mg

Plant nutrients determined as were soil nutrients (Appendix 4).

Digestibility of forage maize

Determination of Neutral Detergent/Cellulase Digestibility

Reagents

1. Acetate buffer: dissolve 1.36 g sodium acetate.3H₂O + 0.6 ml glacial acetic acid in 0.5 litre de-ionised water, make up to 1 litre, mix. Adjust pH to 4.8 with 10% NaOH.
2. Buffered cellulase: weigh 20 g cellulase (derived from *Trichoderma viride*) + 0.1 g chloramphenicol into a 2 litre beaker. Add 1 litre acetate buffer, mix well. Incubate at 40°C for at least 1 h.
3. Neutral detergent: 37.2 g EDTA disodium salt + 13.6 g sodium tetraborate (Borax) + 60 g sodium dodecyl (=lauryl) sulphate + 9.12 g anhydrous disodium hydrogen orthophosphate + 20 ml 2-ethoxyethanol. Dissolve in water, make up to 2 litre with de-ionised water. Adjust pH to 6.9-7.0 with phosphoric acid.
4. Silicone antifoam 30% suspension: dilute 2.5 ml/100 ml water.
5. α -amylase (type XI-A from *Bacillus* species): calculate amount to obtain 1500 units per ml solution. Dissolve amylase in 90 ml de-ionised water. Filter through a No. 1 Whatman filter paper. Add 5 ml 2-ethoxy ethanol and store at 5°C.
6. Acetone - general purpose reagent grade

Method

Weigh (to 3 decimal places) approximately 0.25 g (=W_s) sample into fibre tube. Add 13 ml neutral detergent and 1 ml diluted silicone antifoam. Place tubes in heating block set at 150°C, heat to boil and boil for 30 min shaking frequently. Remove from heat, add 13 ml cold neutral detergent and 1 ml amylase solution. Heat to boiling at about 140°C, boil for a further 30 min.

Filter contents of tubes through sintered crucibles. Wash samples five times with 20 ml hot R.O. water to remove all neutral detergent. Push a bung into base of crucible, add 13 ml hot R.O. water and 1 ml amylase solution. Cap, mix, allow to stand for 15 min, remove bung and filter off solution. Replace bung, add 20 ml buffered cellulase, cap crucible and shake. Incubate for 24 h at $40 \pm 2^\circ\text{C}$, shaking samples twice during incubation. Filter off cellulase by suction, rinsing fibre five times with hot R.O. water and once with acetone. Dry crucibles overnight at $100\text{--}105^\circ\text{C}$. Cool in desiccator and weigh ($=W_3$). Ash crucibles in muffle furnace at 500°C for 4-5 h. Allow crucibles to cool in furnace to 200°C , cool them completely in a desiccator and weight ($=W_4$).

Determination of Dry Matter and Ash

Heat a glass specimen tube to approx. 500°C , cool and weigh ($=W_a$). Weigh into tube 0.5-1.0 g sample, re-weigh ($=W_b$). Place in oven at 105°C for at least 3 h. Allow to cool in desiccator and re-weigh ($=W_c$). Place in muffle furnace at 500°C for at least 3 h. Allow to cool in desiccator and re-weigh ($=W_d$).

$$\% \text{ dry matter (DM)} = [(W_c - W_a) / (W_b - W_a)] * 100$$

$$\% \text{ ash} = [(W_d - W_a) / (W_c - W_a)] * 100$$

$$\% \text{ indigestible organic matter (IOM)} = [(W_3 - W_4) / (W_s * \% \text{DM})] * 10000$$

Neutral detergent/cellulase digestibility (NCD):

$$\% \text{ NCD} = 100 - (\% \text{IOM} + \% \text{ total ash})$$

Appendix 6. Analysis of soil microbial biomass and activity

The Fumigation-Incubation (FI) Method

FI Method to Estimate Microbial Biomass Carbon (BC)

Determination of soil water content

Weigh 20 g fresh soil, oven dry at 105°C for 24 h. Re-weigh samples for dry weight soil (dws).

Soil water content % = (g fresh soil - g dws) / g dws.

Determination of soil water holding capacity (WHC)

Weigh 5 g fresh soil. Put in conical filter funnel fitted with glass wool plug with stem immersed in water 24 h, so that soil absorbs water. Re-weigh.

Soil WHC % = [(g wet soil * 4) - g dws] / g dws * 100.

Method

Weigh 20 g moist sieved soil (55% WHC) into glass beaker. Fumigate soil in large desiccator (30 cm i.d.) lined with moist paper, containing 40 ml CHCl₃ in beaker and few anti-bumping granules. Evacuate desiccator with water pump until CHCl₃ boils vigorously. Close valve, leave desiccator 24 h in the dark at 25°C. Remove paper and CHCl₃. Carry out eight 3-min evacuations in desiccator to remove CHCl₃ from soil. While fumigation in progress, weigh 20 g replicate unfumigated portions of soil (55% WHC) and keep at 25°C in desiccator lined up with moist paper. Incubate fumigated and unfumigated soil: place each beaker of soil in wide-neck screw-top glass confectionery jar, which has 4 ml 1 N NaOH in small glass tube and 4 ml de-ionised water on its bottom, close jar hermetically, put in incubator at 25°C. Include two blank incubations (no soil in jars). Measure CO₂ evolution of unfumigated soils after 24 h, re-add 4 ml 1 N NaOH to small glass tube, re-incubate for a further 9 days. Measure CO₂ evolution of fumigated (10 days incubation) and unfumigated (1+9 days incubation) soils.

CO₂ evolution measurement

Open jar after incubation, add 8 ml 0.75 N BaCl₂ to NaOH. Put solution in beaker with three drops phenolphthalein, titrate with 0.1 N HCl, stirring with magnetic stirrer. Calculate amount of CO₂ evolved during incubation from volume of acid (a) required to bring pH from 8.3 to 3.7 (colour change from fuchsia to white), less that required by blank average (b): 1 ml HCl equivalent to 0.6 mg CO₂-C in NaOH solution.

CO₂ evolution mg.g dws⁻¹ = [(a-b) * 0.6 / dw of 20 g of soil] * 1000

Flush of decomposition (F_c) = CO₂-C evolved by fumigated soil less CO₂-C evolved by unfumigated soil, after 10 days incubation.

BC = F_c / k_c, where k_c = 0.45

Determination of Microbial Activity, as Metabolic Quotient ($q\text{CO}_2$)

$q\text{CO}_2 = \text{CO}_2\text{-C evolved by unfumigated soil after 1 day} / \text{BC}$

FI Method to Estimate Microbial Biomass Nitrogen (BN)

After incubation for BC determination, shake moist soil (20 g) for 1 h with 80 ml 0.5 K_2SO_4 . Filter extract (Whatman filter paper No. 42) and analyse for $\text{NH}_4\text{-N}$ and $\text{NO}_3\text{-N}$ (Appendix 4).

Flush of mineral N (F_n) = ($\text{NH}_4\text{-N} + \text{NO}_3\text{-N}$) from fumigated soil - ($\text{NH}_4\text{-N} + \text{NO}_3\text{-N}$) from unfumigated soil, after 10 days of incubation.

$$\text{BN} = F_n / k_n, \text{ where } k_n = 0.68$$

The Fumigation-Extraction (FE) Method

FE Method for Microbial Biomass Nitrogen (BN) Determination

After 24 h CHCl_3 fumigation, extract soil with 0.5 M K_2SO_4 (as in FI method), and analyse for $\text{NH}_4\text{-N}$ and $\text{NO}_3\text{-N}$ (Appendix 4). Extract unfumigated soil at start of fumigation and analyse in same way.

Extractable N (E_n) = ($\text{NH}_4\text{-N} + \text{NO}_3\text{-N}$) from 24 h-fumigated soil - ($\text{NH}_4\text{-N} + \text{NO}_3\text{-N}$) from unfumigated soil.

$$\text{BN} = E_n / k_n, \text{ where } k_n = 0.54$$

FE Method for Microbial Biomass Carbon (BC) Determination

Extract soil as in BN determination by FE method. Analyse for extractable C (E_c). Determine organic C by digesting 8 ml filtered extract with 2 ml 66.7 mM $\text{K}_2\text{Cr}_2\text{O}_7$, 70 mg HgO and 15 ml of mixture of two parts H_2SO_4 (98% acid) and one part H_3PO_4 (88% acid). Boil mixture gently under reflux for 30 min, allow to cool, dilute with 20-25 ml water added through condenser as rinse. Determine excess dichromate by back titration with 33.3 mM ferrous ammonium sulphate in 0.4 M H_2SO_4 , with 25 mM 1,10-phenanthroline-ferrous sulphate-complex solution (supplied by BDH Ltd.) as indicator. Standardise acidified ferrous ammonium sulphate solution against 66.7 mM $\text{K}_2\text{Cr}_2\text{O}_7$ ('cold blank'). Amount of dichromate consumed is that remaining in blank digestion with 8 ml 0.5 M K_2SO_4 ('hot blank') less that remaining in digest of extract. Extractable C calculated assuming 1 ml 66.7 mM $\text{K}_2\text{Cr}_2\text{O}_7$ equivalent to 1200 mg C.

E_c (mgC.gdws^{-1}) = C extracted from fumigated soil - C extracted from unfumigated soil.

$$\text{BC} = 2.64 E_c$$

Appendix 7. Weed species in field experiments, grouped by growth habit

Vertical (erect) growth habit (G = grass weed; B = broad-leaved weed)

Common name	Latin name	Classification
Couch	<i>Elymus repens</i>	G
Dead-nettle, red	<i>Lamium purpureum</i>	B
Dock	<i>Rumex</i> spp.	B
Fat-hen	<i>Chenopodium album</i>	B
Forget-me-not	<i>Myosotis arvensis</i>	B
Fumitory, common	<i>Fumaria officinalis</i>	B
Hemp-nettle, common	<i>Galeopsis tetrahit</i>	B
Mayweed	<i>Matricaria perforata</i>	B
Meadowgrass, annual	<i>Poa annua</i>	G
Mint, corn	<i>Mentha arvensis</i>	B
Mustard	<i>Brassica</i> spp.	B
Mustard, hedge	<i>Sisymbrium officinale</i>	B
Nettle	<i>Urtica</i> spp.	B
Nightshade, black	<i>Solanum nigrum</i>	B
Oat, spring wild	<i>Avena fatua</i>	G
Plantain	<i>Plantago</i> spp.	B
Poppy, common	<i>Papaver rhoeas</i>	B
Potato, volunteer	<i>Solanum tuberosum</i>	B
Rape, oilseed	<i>Brassica campestris</i> var. <i>oleifera</i>	B
Redshank	<i>Polygonum persicaria</i>	B
Runch (wild radish)	<i>Raphanus raphanistrum</i>	B
Ryegrass, perennial	<i>Lolium perenne</i>	G
Shepherd's purse	<i>Capsella bursa-pastoris</i>	B
Sow-thistle	<i>Sonchus</i> spp.	B
Spurge	<i>Euphorbia</i> spp.	B
Thistle, creeping	<i>Cirsium arvense</i>	B

Horizontal (creeping) growth habit (G = grass weed; B = broad-leaved weed)

Common name	Latin name	Classification
Chickweed, common	<i>Stellaria media</i>	B
Knotgrass	<i>Polygonum aviculare</i>	G
Orache, common	<i>Atriplex patula</i>	B
Pimpernel	<i>Anagallis</i> spp.	B
Speedwell	<i>Veronica</i> spp.	B

Horizontal (climbing) growth habit (B = broad-leaved weed)

Common name	Latin name	Classification
Bindweed, field	<i>Convolvulus arvensis</i>	B
Cleavers	<i>Galium aparine</i>	B

Appendix 8. Weed score in the 1993 field experiment, classified by growth habit

Score according to percentage of subplot area with weed infestation:

0 = weed free; 1 = few weeds, < 20% of area; 2 = 20 - < 40%; 3 = 40 - < 60%;

4 = 60 - < 80%; 5 = 80-100%

Weed score for each subplot in the atrazine-treated main plot only (four replications) - weed species resistant/tolerant to atrazine[‡] (Appendix 7)

additive	Vertical growth habit [‡]				Horizontal growth habit [¥]			
	block 1	block 2	block 3	block 4	block 1	block 2	block 3	block 4
<i>contA</i>	1	0	0	0	1	0	0	0
<i>contB</i>	0	0	0	0	1	0	0	0
<i>N50</i>	0	1	1	0	1	0	0	0
<i>N100</i>	1	0	1	1	1	0	0	0
<i>M50</i>	0	1	0	0	0	0	0	0
<i>M100</i>	1	1	0	0	1	1	0	0
<i>MN50</i>	1	0	0	0	0	0	0	0
<i>MN100</i>	0	0	0	0	2	0	0	0
<i>C50</i>	0	0	1	1	0	0	0	0
<i>C100</i>	0	0	0	0	1	0	0	0
<i>C50m</i>	0	1	0	0	0	0	0	0
<i>C100m</i>	0	0	0	0	0	0	0	0
<i>CN50</i>	1	0	0	0	0	0	0	0
<i>CN100</i>	0	0	0	0	0	0	0	0

[‡]dock, thistle, volunteer potato, grasses

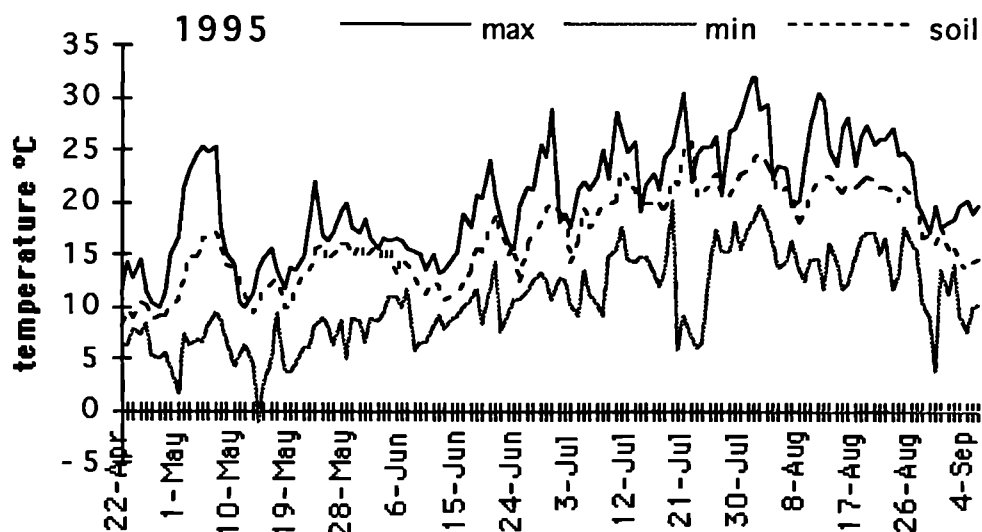
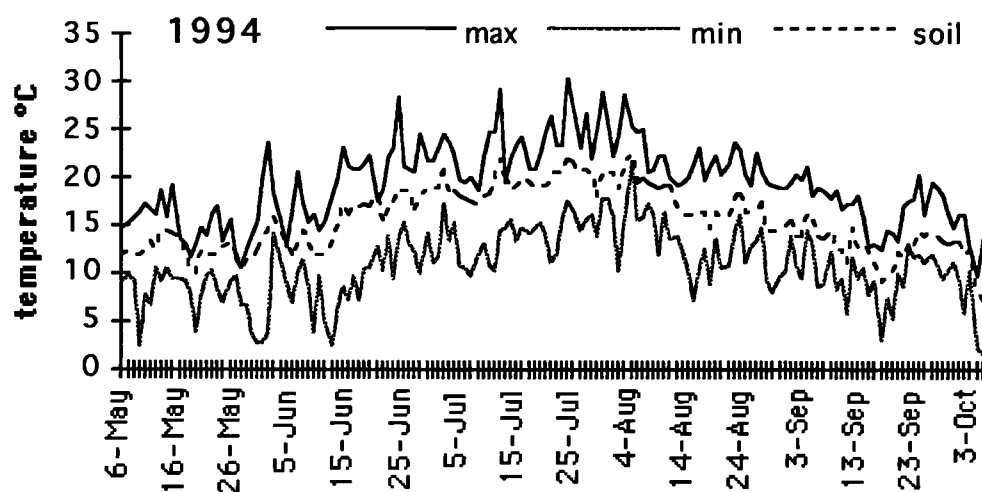
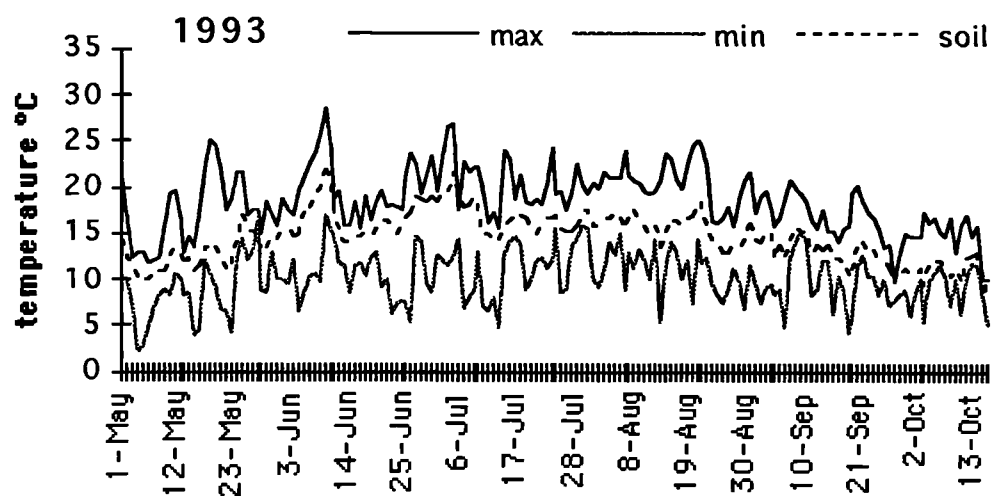
[¥]bindweed, knotgrass

Weed score for each additive in the main plot without atrazine (four replications) - weed species listed in Appendix 7

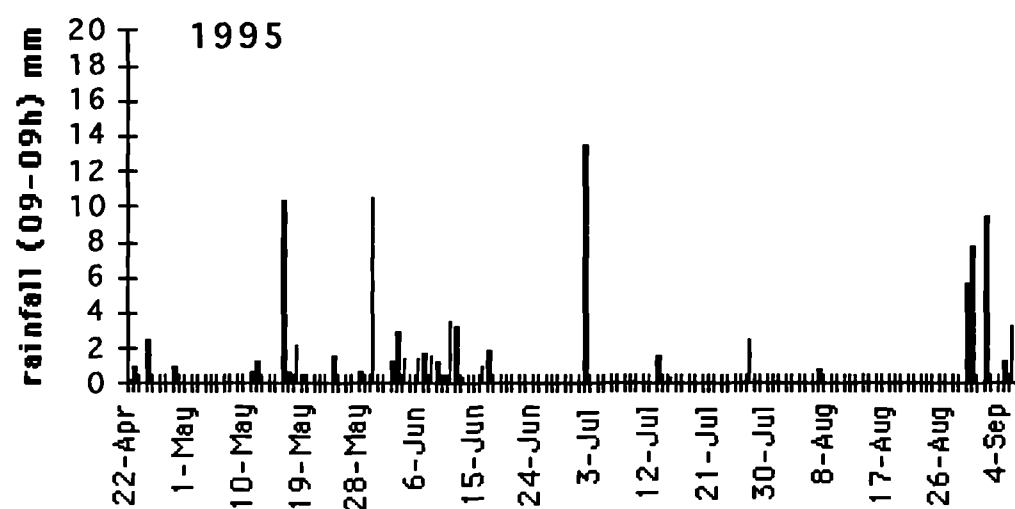
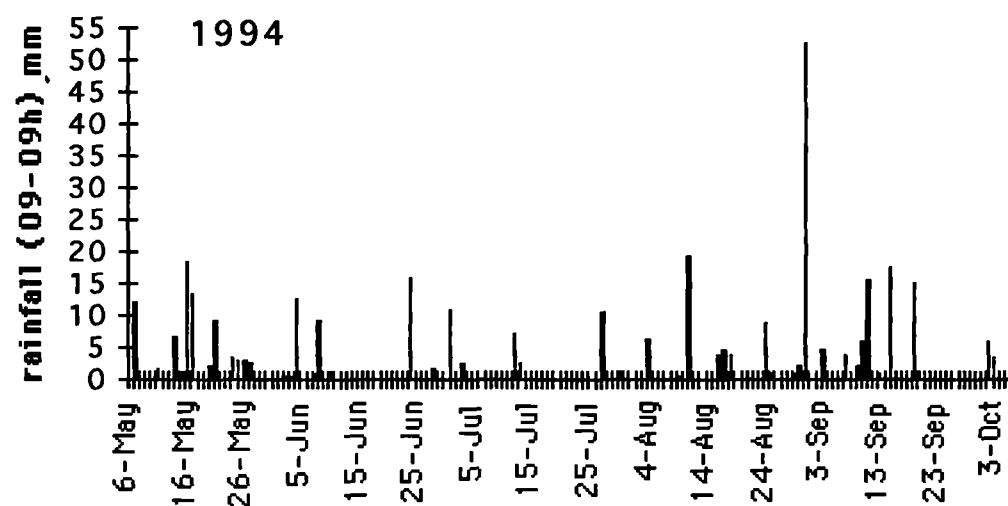
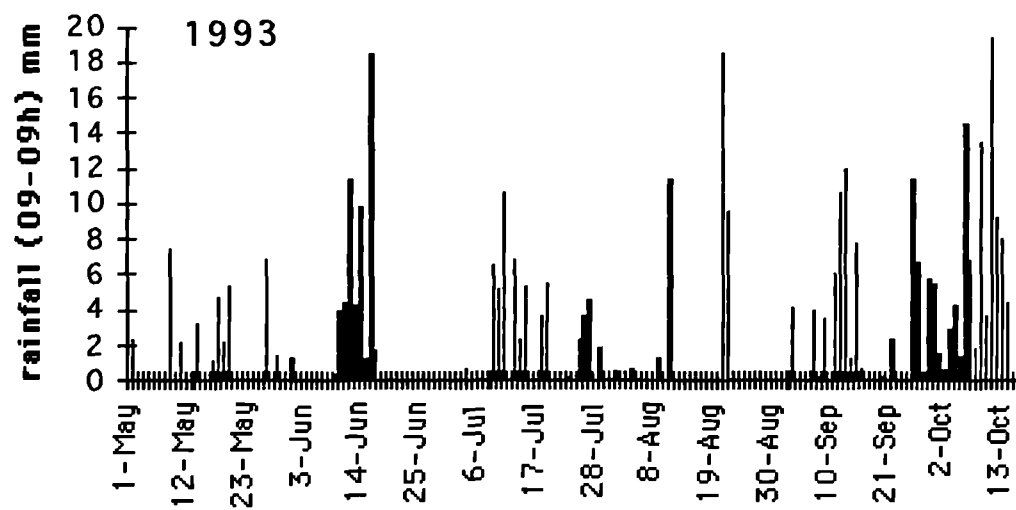
additive	Vertical growth habit				Horizontal growth habit			
	block 1	block 2	block 3	block 4	block 1	block 2	block 3	block 4
<i>contA</i>	3	2	2	2	2	2	2	4
<i>contB</i>	4	3	5	2	1	2	0	5
<i>N50</i>	3	4	2	4	2	1	2	2
<i>N100</i>	4	3	5	4	1	2	0	1
<i>M50</i>	3	3	4	3	1	1	1	4
<i>M100</i>	3	3	3	4	1	2	1	3
<i>MN50</i>	2	4	4	2	3	1	1	3
<i>MN100</i>	3	3	5	3	1	2	1	2
<i>C50</i>	2	5	3	2	1	0	3	4
<i>C100</i>	3	3	2	3	1	2	2	2
<i>C50m</i>	5	5	3	2	1	1	3	3
<i>C100m</i>	4	5	3	3	1	0	3	2
<i>CN50</i>	3	4	5	2	2	1	0	5
<i>CN100</i>	3	3	3	3	2	2	4	3

Appendix 9. 1993-1995 meteorological data in Wye and Viterbo

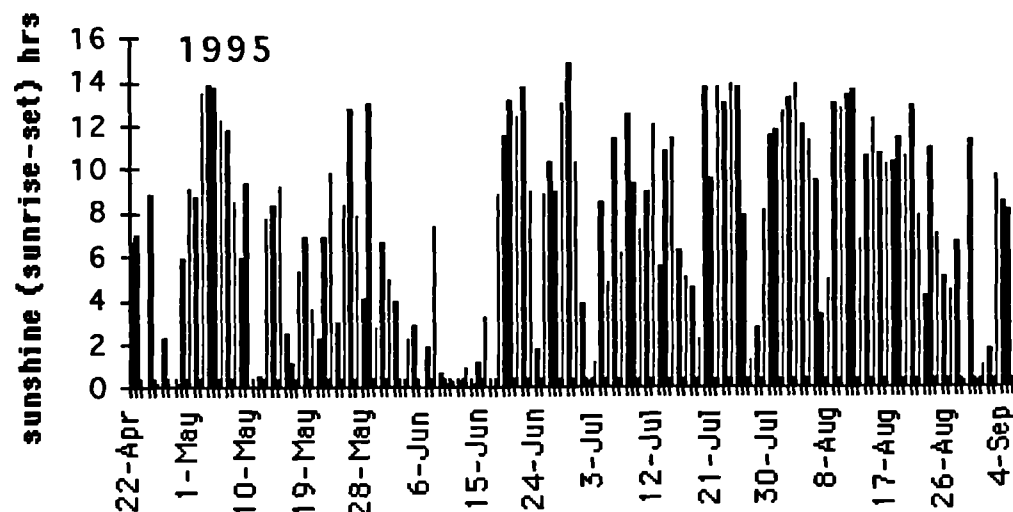
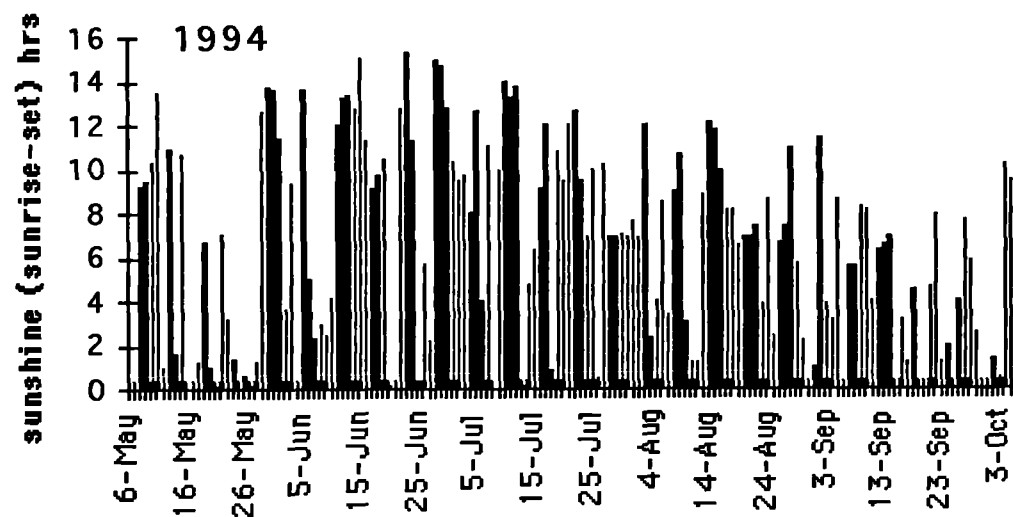
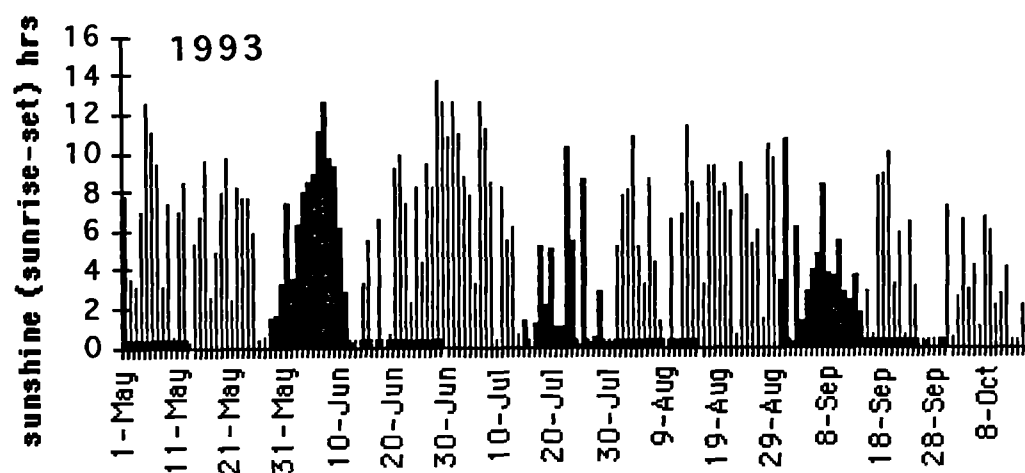
Daily temperatures Wye (°C): air (max & min) and soil (at 10 cm depth, 9am)



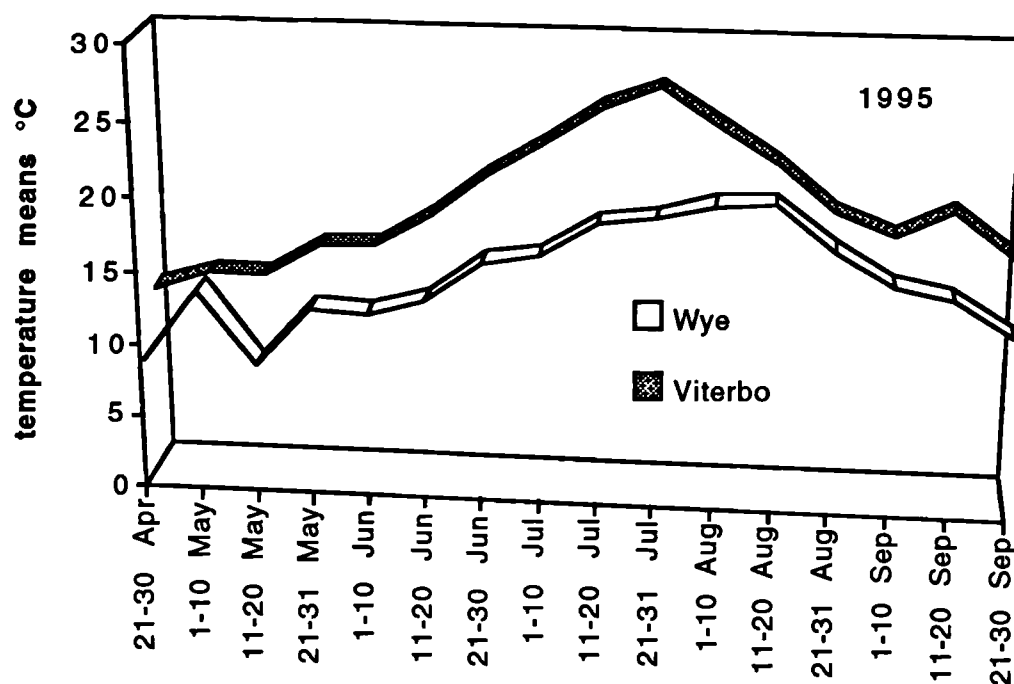
Daily rainfall in Wye (mm) from 9:00 am to 9:00 am



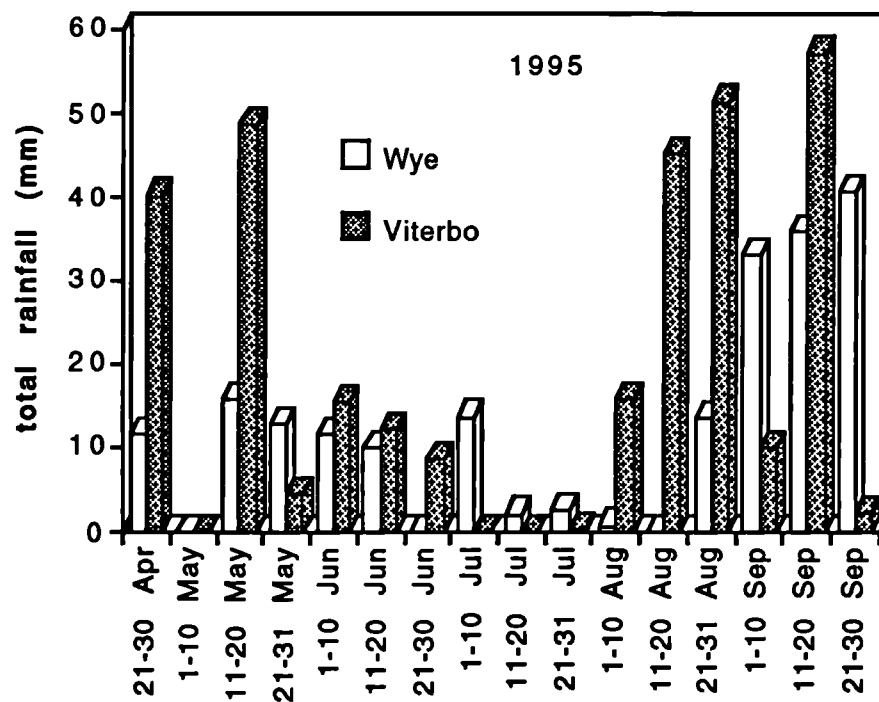
Daily sunshine in Wye (hrs)



Temperature means (°C) in Wye and Viterbo (Italy) during the 1995 field experiments



Total rainfall (mm) in Wye and Viterbo (Italy) during the 1995 field experiments



Appendix 10. Other results of maize DGAs in field experiments

Maize height (cm) with (+ A) and without (- A) atrazine application in the 1993 field experiment

1993 additives	24 Jun (1st DGA)		29 Jul-4 Aug (2nd DGA)		20 Sep (3rd DGA)	
	+ A	- A	+ A	- A	+ A	- A
<i>contA</i>	43.8	48.5	184.9	143.4	229.0	182.1
<i>N100</i>	42.8	46.5	193.4	146.6	220.2	183.2
<i>M100</i>	44.5	49.6	181.9	132.9	229.4	168.9
<i>MN100</i>	46.2	46.7	191.1	145.4	236.3	188.8
<i>C100</i>	47.7	45.9	193.0	151.7	234.8	189.0
<i>C100m</i>	45.6	47.5	192.6	134.4	235.2	160.3
<i>CN100</i>	47.5	49.0	202.2	151.4	231.2	191.9
	<i>add*A</i>	<i>same level A</i>	<i>add*A</i>	<i>same level A</i>	<i>add*A</i>	<i>same level A</i>
SED	2.30	2.30	11.17	10.44	15.33	13.72

Maize stem diameter (mm) with (+ A) and without (- A) atrazine application in the 1993 field experiment

1993 additives	24 Jun (1st DGA)		29 Jul-4 Aug (2nd DGA)		20 Sep (3rd DGA)	
	+ A	- A	+ A	- A	+ A	- A
<i>contA</i>	11.9	13.3	21.7	18.2	19.5	16.6
<i>N100</i>	12.1	12.7	21.3	17.2	20.0	14.5
<i>M100</i>	13.3	13.3	21.3	19.2	20.3	15.8
<i>MN100</i>	13.4	13.3	22.6	17.4	22.1	15.9
<i>C100</i>	13.8	13.4	22.6	19.3	20.4	16.3
<i>C100m</i>	13.4	13.6	23.7	18.6	21.5	15.8
<i>CN100</i>	13.9	13.4	23.7	19.1	22.0	16.4
	<i>add*A</i>	<i>same level A</i>	<i>add*A</i>	<i>same level A</i>	<i>add*A</i>	<i>same level A</i>
SED	0.71	0.70	1.01	0.99	1.37	1.23

Maize fresh biomass production (kg.m⁻²) with (+ A) and without (- A) atrazine application in the 1993 field experiment

1993 additives	24 Jun (1st DGA)		29 Jul-4 Aug (2nd DGA)		20 Sep (3rd DGA)	
	+ A	- A	+ A	- A	+ A	- A
<i>contA</i>	0.29	0.29	4.7	3.5	8.5	6.1
<i>N100</i>	0.25	0.30	5.1	3.5	9.6	6.5
<i>M100</i>	0.25	0.33	5.4	3.1	8.6	5.1
<i>MN100</i>	0.35	0.30	5.5	3.4	9.7	6.6
<i>C100</i>	0.37	0.29	5.5	3.8	10.3	5.9
<i>C100m</i>	0.26	0.34	6.1	3.0	9.2	5.1
<i>CN100</i>	0.39	0.34	6.1	4.0	10.1	6.8
	<i>add*A</i>	<i>same level A</i>	<i>add*A</i>	<i>same level A</i>	<i>add*A</i>	<i>same level A</i>
SED	0.058	0.059	0.65	0.48	1.48	1.03

Maize fresh biomass production (kg.m⁻²) in 1994 Field A experiment

1994 treatment	28 July (1st DGA)		13 September (2nd DGA)	
	fresh weight†	log fr weight	fresh weight†	log fr weight
<i>cont+</i>	0.98	0.29	2.98	0.60
<i>cont-</i>	0.17	0.07	0.37	0.13
<i>N100+</i>	0.94	0.28	4.46	0.74
<i>N100-</i>	0.36	0.13	0.52	0.18
<i>N200+</i>	1.37	0.36	4.67	0.75
<i>C100+</i>	0.74	0.24	2.71	0.57
<i>C100-</i>	0.18	0.07	0.26	0.10
<i>C200+</i>	1.28	0.36	4.71	0.76
SED		0.049		0.039

†statistical analysis carried out on logarithmically transformed data (*log fr weight*)

Maize fresh biomass production (kg.m⁻²) with forage maize cultivars *Aziz* and *LG2080* in the 1994 Field B experiment

1994 additives	7 Jul (1st DGA)		3 Aug (2nd DGA)		6 Sep (3rd DGA)	
	<i>Aziz</i>	<i>LG2080</i>	<i>Aziz</i>	<i>LG2080</i>	<i>Aziz</i>	<i>LG2080</i>
<i>cont</i>	1.03	0.75	4.8	5.0	6.6	7.1
<i>N50</i>	0.81	0.70	4.8	5.1	6.7	7.7
<i>N100</i>	0.83	0.71	5.1	5.1	7.0	7.8
<i>C50</i>	0.96	1.13	4.9	4.8	6.9	8.2
<i>C100</i>	0.84	1.01	5.3	5.8	6.9	8.5
<i>additive*</i>						
	<i>cultivar</i>	<i>within cv.</i>	<i>add*cv.</i>	<i>within cv.</i>	<i>add*cv.</i>	<i>within cv.</i>
SED	0.201	0.142	0.59	0.42	0.89	0.63

Maize fresh biomass production (kg.m⁻²) in the 1995 *Field 1 year* and *2 years* experiments (Wye)

1995 additive	10 Jul (1st DGA)		8 Aug (2nd DGA)		25 Aug (3rd DGA)	
	<i>1 year</i>	<i>2 years</i>	<i>1 year</i>	<i>2 years</i>	<i>1 year</i>	<i>2 years</i>
<i>cont+</i>	0.77	0.61	3.0	3.1	3.6	3.9
<i>cont-</i>	0.52	0.40	1.9	1.0	1.9	1.2
<i>N100+</i>	0.81	0.63	4.3	4.4	4.3	3.9
<i>N100-</i>	0.83	0.48	2.6	1.3	2.3	1.9
<i>N200+</i>	0.88	0.66	4.1	3.9	4.2	4.3
<i>C100+</i>	0.83	0.75	3.4	4.1	3.6	4.5
<i>C100-</i>	0.51	0.49	1.5	1.2	1.5	1.1
<i>C200+</i>	0.75	1.02	3.8	4.3	4.7	4.7
SED	0.129	0.121	0.54	0.33	0.44	0.47