

CARBON DYNAMICS AND NITROGEN MINERALIZATION IN SOIL UNDER ELEVATED ATMOSPHERIC CO₂ CONDITIONS

THULASI, V.

T7577



I.A.R.I



DIVISION OF SOIL SCIENCE AND AGRICULTURAL CHEMISTRY
INDIAN AGRICULTURAL RESEARCH INSTITUTE
NEW DELHI-110 012, INDIA

2005

T- 7577

**CARBON DYNAMICS AND NITROGEN
MINERALIZATION IN SOIL UNDER ELEVATED
ATMOSPHERIC CO₂ CONDITIONS**

By
THULASI, V.

A Thesis
submitted to the Post Graduate School,
Indian Agricultural Research Institute, New Delhi,
in partial fulfilment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

in

SOIL SCIENCE AND AGRICULTURAL CHEMISTRY

2005

Approved by:
Chairman

:



Dr. Deo Pal

Co-Chairman

:



Dr. S.C. Datta

Members

1.

:


Dr. Subhendu Bhadraray

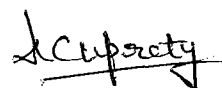
2.

:


Dr. Tapan J. Purakayastha

3.

:



Dr. D.C. Uprety

4.

:



Dr. Naveen Kalra



7-7577

Dedicated
To My
Ammamma and Achamma

ACKNOWLEDGEMENT

I humbly bow my head before Lord Almighty for blessing me with power, health and confidence to undertake and complete this venture.

It is indeed a matter of great privilege and esteem for me to express my deep sense of gratitude, indebtedness and obedience to my benevolent major advisor, Dr. Deo Pal whose vision was the guiding light of this investigation. His erudite guidance, amazing patience, encouraging attitude, timely help and warm concern have enabled me in the satisfactory completion of the arduous task. I venerate the splendid personality with reverence and reverberation.

No word of appreciation would be sufficient to express my heartiest feelings towards Dr. S C Datta, co-chairman of my advisory committee for his persistent involvement, scholarly suggestions, cooperation and genuine help during the course of this investigation.

I would always like to remember the help offered by Dr. Subhendu Bhadraray, member of my advisory committee who was at his toes to share his enormous knowledge and precious time. It is my pleasure to extend my sincere obligations and deep sense of gratitude to him for his persistent support, accurate planning, valuable suggestions, catalytic comments, convincing criticisms and spectacular guidance which helped a lot to push this ever cherished dream into reality.

I wish to place on record my profound gratitude and sincere obligations to Dr. Tapan Jyoti Purakayastha, member of my advisory committee for his constant encouragement, venerated guidance, copious support and critical suggestions which, of course made my research a smooth ride.

I also avail this opportunity to pay my heartfelt thanks to Dr. P K Chhonkar, Head of the division for his precious advice, immense help and valuable suggestions and also for providing the necessary facilities for the investigation.

I deem it as a pleasure to convey my sincere thanks to Dr. G Narayanasamy, Professor of the division for his wholehearted co-operation, great help and austere supervision, which helped a lot in completing the PhD programme in time.

Candid thanks are due to Dr. D C Uprety and Dr Naveen Kalra, members of my advisory committee for their expert guidance, extreme help and cordial behavior.

My profound thanks to Dr. Madan Pal, and Dr. Rajender Singh for their propitious support, materialistic help and critical suggestions during the research programme. I am highly thankful to Patra sir, Gurbux Singhji, K P Singhji, Sharma sir, Vijay Verma sir, Mehra sir, Kaushik sir, for the help rendered during the investigation. I thankfully acknowledge the help provided by Dr. Kaim, Mr. Mohan Lal and Jagdeesh ji of Nuclear Research Laboratory in carrying out the analytical works. I am extremely grateful to Dr. Aggarwaal, Ved Prakash

Kaushik sir, Usha madam, Ram Rathian ji, Namdev ji, Mahesh ji and Sivnarayan ji for their cooperation and encouragement.

I honestly acknowledge the wholehearted co-operation and sincere help rendered by all other teaching and non-teaching staff of my Department. My sincere and profound thanks are due to the labourers of the division of Plant Physiology and Soil Science for their selfless help during the course of this investigation.

Profound thanks to all my juniors, seniors, and my colleagues especially, Jyoti didi, Sandeep, Amit, Deb Tanu Sir, Sangeetha didi, Behra sir, Thanga samy, Asit, Reza, Manoj, Binoy, Bindu, Ashish sir, Karthikeyan sir, Siva Prasad sir and Bipash whose concern was always there with me.

The care and affection rendered by Deo Pal sir's and Tapan sir's families, and the moments with Sayori and Oishani will always remain in mind as colourful dreams.

It would become too formal if I acknowledge the sincere help, support and encouragement offered by my friends Push, Sari, Jinu, Sumiya, Thasni, Soumia and Renji during my life at IARI.

Smithechi and Radhu, I have really enjoyed their pleasant amity during my days at Mandakini.

Shareefa, Anu, Letha, Panki, Suma, Kalyani, Betsy, Subi, Lekshmy, Araty, Jainy, Hema, Anu, Manju, Nimisha, Dhanya, Adhini, Anu, Nisha, Prabha, Remya, Malathi akka, Sherry, Madhumita, Sibi, Anita, Rakhee, Partha, Sunilettan, Varky, Bibin, Anoop, Anees, all others in PUMA, Sharmishta, ... all my friends have added dazzling smiles and happiness to my life at IARI.

Above all, the warm wishes, unfailing support, flying encouragement, and blessings extended by my dear Achan, Amma, Nteya, Amma, Oppa, uncles, aunties, and other relatives have silently worked in enabling me to deal this endeavor. The love and affection of my sister, Kavitha was always with me. She is always there, close to my heart, and I really grope for words to express my feelings towards her.

No word can truly portray my indebtedness, and love towards Rajesh, my husband for his mental support, affection, timely help, earnest assistance, encouragement and zeal rendered in each moment of my life.

A special word of thanks to Siva and Ashok Computers for the help rendered while typing the manuscript.

The award of CSIR-UGC fellowship is gratefully acknowledged.

New Delhi

Thulasi
(Thulasi, V.)

CONTENTS

Sl. No.	Title	Page No.
1.	INTRODUCTION	1-6
2.	REVIEW OF LITERATURE	7-37
	2.1 Rise in atmospheric CO ₂	7-10
	2.2 Carbon dioxide enrichment technologies	10-14
	2.3 Crop responses to elevated CO ₂	14-24
	2.4 Soil changes	24-31
	2.5 Litter quality and decomposition under elevated CO ₂	31-34
	2.6 Modelling the responses to elevated CO ₂	34-36
	2.7 Carbon dioxide response studies in India	36-37
3.	MATERIALS AND METHODS	38-61
	3.1 Experimental site	38
	3.2 Pot culture experiment	38-44
	3.3 Field experiment	44-49
	3.4 Decomposition study	49-53
	3.5 Analytical procedures	53-57
	3.6 Initial characteristics of the experimental soils	57-58
	3.7 CERES-N model	58-60
	3.8 Statistical analysis	60-61
4.	RESULTS AND DISCUSSION	62-134
	4.1 Pot culture study – Rice and wheat	62-95
	4.2 Field experiment – Rice and wheat	95-106
	4.3 Decomposition study – Rice and wheat residues	107-116
	4.4 Simulation of decomposition using CERES model	116-123
	4.5 General discussion	123-134
5.	SUMMARY AND CONCLUSION	135-143
	REFERENCES	i-xxi
	APPENDIX	I-II

LIST OF TABLES

Table No.	Table	After page
1	Initial characteristics of the experimental soils used for pot culture study in OTCs	39
2	Initial characteristics of the experimental soils used for raising crops in field (FACE)	44
3	Initial carbon pools (depth wise) of the experimental soils used for raising crops in field (FACE)	44
4	Initial characteristics of the soil used for decomposition study in phytotron chambers	49
5	Initial characteristics of the residues used for decomposition study in phytotron chambers	49
6	Stem dry matter yield (g pot^{-1}) of rice grown in OTC as influenced by the interaction of levels of CO_2 and stages of crop growth	64
7	Leaf dry matter yield (g pot^{-1}) of rice grown in OTC as influenced by the interaction of levels of CO_2 and stages of crop growth	65
8	Root dry matter yield (g pot^{-1}) of rice grown in OTC as influenced by the interaction of levels of CO_2 and stages of crop growth	65
9	Total dry matter yield (g pot^{-1}) of rice grown in OTC as influenced by the interaction of levels of CO_2 and stages of crop growth	66
10	Fresh root weight (g pot^{-1}) of rice grown in OTC as influenced by the interaction of levels of CO_2 and stages of crop growth	67
11	Root volume (ml pot^{-1}) of rice grown in OTC as influenced by the interaction of levels of CO_2 and stages of crop growth	68
12	Carbon uptake (mg pot^{-1}) by stem dry matter of rice grown in OTC as influenced by the interaction of levels of CO_2 and stages of crop growth	68
13	Carbon uptake (mg pot^{-1}) by leaf dry matter of rice grown in OTC as influenced by the interaction of levels of CO_2 and stages of crop growth	69
14	Root carbon concentration (per cent) in rice grown in OTC as influenced by the interaction of levels of CO_2 and stages of crop growth	70
15	Carbon uptake (mg pot^{-1}) by roots of rice grown in OTC as influenced by the interaction of levels of CO_2 and stages of crop growth	70

List of Table cont...

List of Table cont...

Table No.	Table	After page
16	Total carbon uptake (mg pot ⁻¹) by rice grown in OTC as influenced by the interaction of levels of CO ₂ and stages of crop growth	71
17	Microbial biomass carbon (MBC, mg kg ⁻¹) in rice rhizosphere at OTC as influenced by the interaction of levels of CO ₂ and stages of crop growth	73
18	Dissolved organic carbon (DOC, mg kg ⁻¹) in rice rhizosphere at OTC as influenced by the interaction of levels of CO ₂ and stages of crop growth	74
19	Carbohydrate carbon (CHC, mg kg ⁻¹) in rice rhizosphere at OTC as influenced by the interaction of levels of CO ₂ and stages of crop growth	75
20	Labile carbon (LBC, mg kg ⁻¹) in rice rhizosphere at OTC as influenced by the interaction of levels of CO ₂ and stages of crop growth	76
21	Total soil carbon (TSC, g kg ⁻¹) in rice rhizosphere at OTC as influenced by elevated CO ₂ at different stages of crop growth	77
22	Ammoniacal nitrogen (mg kg ⁻¹) contents in rice rhizosphere soil at OTC as influenced by the interaction of levels of CO ₂ and stages of crop growth	77
23	Nitrate nitrogen (mg kg ⁻¹) contents in rice rhizosphere soil at OTC as influenced by the interaction of levels of CO ₂ and stages of crop growth	77
24	Stem dry matter yield (g pot ⁻¹) of wheat grown in OTC as influenced by the interaction of levels of CO ₂ and stages of crop growth	78
25	Leaf dry matter yield (g pot ⁻¹) of wheat grown in OTC as influenced by the interaction of levels of CO ₂ and stages of crop growth	78
26	Root dry matter yield (g pot ⁻¹) of wheat grown in OTC as influenced by the interaction of levels of CO ₂ and stages of crop growth	79
27	Total dry matter yield (g pot ⁻¹) of wheat grown in OTC as influenced by the interaction of levels of CO ₂ and stages of crop growth	80
28	Fresh root weight (g pot ⁻¹) of wheat grown in OTC as influenced by the interaction of levels of CO ₂ and stages of crop growth	81
29	Root volume (ml pot ⁻¹) of wheat grown in OTC as influenced by the interaction of levels of CO ₂ and stages of crop growth	81

List of Table cont...

List of Table cont...

Table No.	Table	After page
30	Stem carbon concentration (per cent) in wheat grown in OTC as influenced by the interaction of levels of CO ₂ and stages of crop growth	82
31	Carbon uptake (mg pot ⁻¹) by stem dry matter of wheat grown in OTC as influenced by the interaction of levels of CO ₂ and stages of crop growth	82
32	Carbon uptake (mg pot ⁻¹) by leaf dry matter of wheat grown in OTC as influenced by the interaction of levels of CO ₂ and stages of crop growth	83
33	Carbon uptake (mg pot ⁻¹) by roots of wheat grown in OTC as influenced by the interaction of levels of CO ₂ and stages of crop growth	84
34	Total carbon uptake (mg pot ⁻¹) by wheat grown in OTC as influenced by the interaction of levels of CO ₂ and stages of crop growth	84
35	Microbial biomass carbon (MBC, mg kg ⁻¹) in wheat rhizosphere at OTC as influenced by the interaction of levels of CO ₂ and stages of crop growth	87
36	Dissolved organic carbon (DOC, mg kg ⁻¹) in wheat rhizosphere at OTC as influenced by the interaction of levels of CO ₂ and stages of crop growth	88
37	Carbohydrate carbon (CHC, mg kg ⁻¹) in wheat rhizosphere at OTC as influenced by the interaction of levels of CO ₂ and stages of crop growth	88
38	Labile carbon (LBC, mg kg ⁻¹) in wheat rhizosphere at OTC as influenced by the interaction of levels of CO ₂ and stages of crop growth	89
39	Total soil carbon (TSC, g kg ⁻¹) in wheat rhizosphere at OTC as influenced by elevated CO ₂ at different stages of crop growth	90
40	Ammoniacal nitrogen (mg kg ⁻¹) contents in wheat rhizosphere soil at OTC as influenced by the interaction of levels of CO ₂ and stages of crop growth	90
41	Nitrate nitrogen (mg kg ⁻¹) contents in wheat rhizosphere soil at OTC as influenced by the interaction of levels of CO ₂ and stages of crop growth	90
42	Step wise regression equations of active carbon and inorganic nitrogen pools in rhizospheres soils in OTC as a function of various plant related parameters	93
43	Carbohydrate carbon in soil during rice growth under FACE as influenced by the three way interaction between levels of CO ₂ , stages of crop growth and depths of soil	99

List of Table cont...

Table No.	Table	After page
44	Carbohydrate carbon in soil during wheat growth under FACE as influenced by the three way interaction between levels of CO ₂ , stages of crop growth and depths of soil	103
45	Per cent changes in microbial biomass carbon in soil at different depths at various stages of rice growth as affected by elevation of CO ₂ under FACE	106
46	Per cent changes in dissolved organic carbon in soil at different depths at various stages of rice growth as affected by elevation of CO ₂ under FACE	106
47	Per cent changes in carbohydrate carbon in soil at different depths at various stages of rice growth as affected by elevation of CO ₂ under FACE	106
48	Per cent changes in labile carbon in soil at different depths at various stages of rice growth as affected by elevation of CO ₂ under FACE	106
49	Per cent changes in microbial biomass carbon in soil at different depths at various stages of wheat growth as affected by elevation of CO ₂ under FACE	106
50	Per cent changes in dissolved organic carbon in soil at different depths at various stages of wheat growth as affected by elevation of CO ₂ under FACE	106
51	Per cent changes in carbohydrate carbon in soil at different depths at various stages of wheat growth as affected by elevation of CO ₂ under FACE	106
52	Per cent changes in labile carbon in soil at different depths at various stages of wheat growth as affected by elevation of CO ₂ under FACE	106
53	Modified decay parameters for the three plant residue pools in CERES model obtained by fitting to the experimental results	117
54	Input values of different types of residues used for running the model	117

LIST OF FIGURES

Fig. No.	Figures	After page
1	Schematic diagram of major feedback processes in a coupled climate carbon cycle system	10
2	Schematic representation of carbon partitioning showing major processes	23
3	Conceptual diagram highlighting the potential consequences of changing atmospheric CO ₂ concentration	27
4	Basic schematic depiction and a representative diagram of Open top chamber (OTC) technology	39
5	Layout schematic of mid FACE facility	45
6	The conceptual structure of organic C/N pools used in the CERES model	59
7	Stem dry matter yield (g pot ⁻¹) of rice grown in OTC as influenced by a) levels of CO ₂ and b) stages of growth	64
8	Leaf dry matter yield (g pot ⁻¹) of rice grown in OTC as influenced by a) levels of CO ₂ and b) stages of growth	65
9	Root dry matter yield (g pot ⁻¹) of rice grown in OTC as influenced by a) levels of CO ₂ and b) stages of growth	65
10	Grain weight (g pot ⁻¹) of rice grown in OTC as influenced by the elevation of atmospheric CO ₂ concentration	66
11	Total dry matter yield (g pot ⁻¹) of rice grown in OTC as influenced by a) levels of CO ₂ and b) stages of growth	66
12	Biomass partitioning to different plant parts at various stages of rice grown in OTC as affected by elevation of atmospheric CO ₂ concentration	66
13	Fresh root weight (g pot ⁻¹) of rice grown in OTC as influenced by a) levels of CO ₂ and b) stages of growth	67
14	Root volume (ml pot ⁻¹) of rice grown in OTC as influenced by a) levels of CO ₂ and b) stages of growth	68
15	Stem carbon concentration (per cent) in rice grown in OTC as influenced by a) levels of CO ₂ and b) stages of growth	68
16	Carbon uptake (mg pot ⁻¹) by stem dry matter of rice grown in OTC as influenced by a) levels of CO ₂ and b) stages of growth	68
17	Leaf carbon concentration (per cent) in rice grown in OTC as influenced by a) levels of CO ₂ and b) stages of growth	69

List of Figures cont...

List of Figures cont...

Fig. No.	Figures	After page
18	Carbon uptake (mg pot ⁻¹) by leaves of rice grown in OTC as influenced by a) levels of CO ₂ and b) stages of growth	69
19	Root carbon concentration (per cent) in rice grown in OTC as influenced by a) levels of CO ₂ and b) stages of growth	70
20	Carbon uptake (mg pot ⁻¹) by roots of rice grown in OTC as influenced by a) levels of CO ₂ and b) stages of growth	70
21	Carbon concentration (per cent) in the grains of rice grown in OTC as influenced by the elevation of atmospheric CO ₂ concentration	71
22	Carbon uptake (mg pot ⁻¹) by the grains of rice grown in OTC as influenced by the elevation of atmospheric CO ₂ concentration	71
23	Total carbon uptake (mg pot ⁻¹) by rice crop grown in OTC as influenced by a) levels of CO ₂ and b) stages of growth	71
24	Carbon partitioning to different plant parts at various stages of rice growth in OTC as affected by elevation of atmospheric CO ₂ concentration	71
25	Nitrogen concentration (per cent) in the stem dry matter of rice grown in OTC as influenced by a) levels of CO ₂ and b) stages of growth	72
26	The C:N ratio of stem dry matter of rice grown in OTC as influenced by a) levels of CO ₂ and b) stages of growth	72
27	Nitrogen concentration (per cent) in the leaves of rice grown in OTC as influenced by a) levels of CO ₂ and b) stages of growth	72
28	The C:N ratio of leaves of rice grown in OTC as influenced by a) levels of CO ₂ and b) stages of growth	72
29	Nitrogen concentration (per cent) in the roots of rice grown in OTC as influenced by a) levels of CO ₂ and b) stages of growth	72
30	The C:N ratio of roots of rice grown in OTC as influenced by a) levels of CO ₂ and b) stages of growth	72
31	Nitrogen concentration (per cent) in the grains of rice grown in OTC as influenced by the elevation of atmospheric CO ₂ concentration	73
32	The C:N ratio of grains of rice grown in OTC as influenced by the elevation of atmospheric CO ₂ concentration	73
33	Microbial biomass carbon (MBC, mg kg ⁻¹) in rice rhizosphere at OTC as influenced by a) levels of CO ₂ and b) stages of growth	73
34	Dissolved organic carbon (DOC, mg kg ⁻¹) in rice rhizosphere at OTC as influenced by a) levels of CO ₂ and b) stages of	74

List of Figures cont...
growth

Fig. No.	Figures	After page
35	Carbohydrate carbon (CHC, mg kg ⁻¹) in rice rhizosphere at OTC as influenced by a) levels of CO ₂ and b) stages of growth	75
36	Labile carbon (LBC, mg kg ⁻¹) in rice rhizosphere at OTC as influenced by a) levels of CO ₂ and b) stages of growth	76
37	Ammoniacal nitrogen (mg kg ⁻¹) in rice rhizospheres soil at OTC as influenced by a) levels of CO ₂ and b) stages of growth	77
38	Nitrate nitrogen (mg kg ⁻¹) in rice rhizospheres soil at OTC as influenced by a) levels of CO ₂ and b) stages of growth	77
39	Stem dry matter yield (g pot ⁻¹) of wheat grown in OTC as influenced by a) levels of CO ₂ and b) stages of growth	78
40	Leaf dry matter yield (g pot ⁻¹) of wheat grown in OTC as influenced by a) levels of CO ₂ and b) stages of growth	78
41	Root dry matter yield (g pot ⁻¹) of wheat grown in OTC as influenced by a) levels of CO ₂ and b) stages of growth	79
42	Grain weight (g pot ⁻¹) of wheat grown in OTC as influenced by the elevation of atmospheric CO ₂ concentration	79
43	Total dry matter yield (g pot ⁻¹) of wheat grown in OTC as influenced by a) levels of CO ₂ and b) stages of growth	79
44	Biomass partitioning to different plant parts at various stages of wheat grown in OTC as affected by elevation of atmospheric CO ₂ concentration	80
45	Fresh root weight (g pot ⁻¹) of wheat grown in OTC as influenced by a) levels of CO ₂ and b) stages of growth	81
46	Root volume (ml pot ⁻¹) of wheat grown in OTC as influenced by a) levels of CO ₂ and b) stages of growth	81
47	Stem carbon concentration (per cent) in wheat grown in OTC as influenced by a) levels of CO ₂ and b) stages of growth	82
48	Carbon uptake (mg pot ⁻¹) by stem dry matter of wheat grown in OTC as influenced by a) levels of CO ₂ and b) stages of growth	82
49	Leaf carbon concentration (per cent) in wheat grown in OTC as influenced by a) levels of CO ₂ and b) stages of growth	83
50	Carbon uptake (mg pot ⁻¹) by leaves of wheat grown in OTC as influenced by a) levels of CO ₂ and b) stages of growth	83
51	Root carbon concentration (per cent) in wheat grown in OTC as influenced by a) levels of CO ₂ and b) stages of growth	83

List of Figures cont...

Fig. No.	Figures	After page
52	Carbon uptake (mg pot^{-1}) by roots of wheat grown in OTC as influenced by a) levels of CO_2 and b) stages of growth	84
53	Carbon concentration (per cent) in the grains of wheat grown in OTC as influenced by the elevation of atmospheric CO_2 concentration	84
54	Carbon uptake (mg pot^{-1}) by the grains of wheat grown in OTC as influenced by the elevation of atmospheric CO_2 concentration	84
55	Total carbon uptake (mg pot^{-1}) by wheat crop grown in OTC as influenced by a) levels of CO_2 and b) stages of growth	84
56	Carbon partitioning to different plant parts at various stages of wheat growth in OTC as affected by elevation of atmospheric CO_2 concentration	85
57	Nitrogen concentration (per cent) in the stem dry matter of wheat grown in OTC as influenced by a) levels of CO_2 and b) stages of growth	85
58	The C:N ratio of stem dry matter of wheat grown in OTC as influenced by a) levels of CO_2 and b) stages of growth	85
59	Nitrogen concentration (per cent) in the leaves of wheat grown in OTC as influenced by a) levels of CO_2 and b) stages of growth	86
60	The C:N ratio of leaves of wheat grown in OTC as influenced by a) levels of CO_2 and b) stages of growth	86
61	Nitrogen concentration (per cent) in the roots of wheat grown in OTC as influenced by a) levels of CO_2 and b) stages of growth	86
62	The C:N ratio of roots of wheat grown in OTC as influenced by a) levels of CO_2 and b) stages of growth	86
63	Nitrogen concentration (per cent) in the grains of wheat grown in OTC as influenced by the elevation of atmospheric CO_2 concentration	86
64	The C:N ratio of grains of wheat grown in OTC as influenced by the elevation of atmospheric CO_2 concentration	86
65	Microbial biomass carbon (MBC, mg kg^{-1}) in wheat rhizosphere at OTC as influenced by a) levels of CO_2 and b) stages of growth	87
66	Dissolved organic carbon (DOC, mg kg^{-1}) in wheat rhizosphere at OTC as influenced by a) levels of CO_2 and b) stages of growth	88

List of Figures cont...

List of Figures cont...

Fig. No.	Figures	After page
67	Carbohydrate carbon (CHC, mg kg ⁻¹) in wheat rhizosphere at OTC as influenced by a) levels of CO ₂ and b) stages of growth	88
68	Labile carbon (LBC, mg kg ⁻¹) in wheat rhizosphere at OTC as influenced by a) levels of CO ₂ and b) stages of growth	89
69	Ammoniacal nitrogen (mg kg ⁻¹) in wheat rhizospheres soil at OTC as influenced by a) levels of CO ₂ and b) stages of growth	90
70	Nitrate nitrogen (mg kg ⁻¹) in wheat rhizospheres soil at OTC as influenced by a) levels of CO ₂ and b) stages of growth	90
71	Per cent increase in different active carbon pools in rhizospheres soils of both rice and wheat grown in OTCs as influenced by elevation of CO ₂	91
72	Increase (per cent over initial values) in different active carbon pools in rhizospheres soils at OTC at the end of respective crop as affected by elevation of CO ₂	92
73	Relative increase (per cent) in different active carbon pools (averaged over the crop growth stages) in rhizospheres of the test crops as affected by elevation of CO ₂	92
74	Microbial biomass carbon (MBC, mg kg ⁻¹) in soil during rice growth under FACE as influenced by the main effects of a) levels of CO ₂ , b) stages of growth and c) depths of soil	96
75	Microbial biomass carbon (MBC, mg kg ⁻¹) in soil during rice growth under FACE as affected by a) CO ₂ x stage interaction and b) CO ₂ x depth interaction	97
76	Dissolved organic carbon (DOC, mg kg ⁻¹) in soil during rice growth under FACE as influenced by the main effects of a) levels of CO ₂ , b) stages of growth and c) depths of soil	97
77	Dissolved organic carbon (DOC, mg kg ⁻¹) in soil during rice growth under FACE as affected by a) CO ₂ x stage interaction and b) CO ₂ x depth interaction	98
78	Carbohydrate carbon (CHC, mg kg ⁻¹) in soil during rice growth under FACE as influenced by the main effects of a) levels of CO ₂ , b) stages of growth and c) depths of soil	98
79	Carbohydrate carbon (CHC, mg kg ⁻¹) in soil during rice growth under FACE as affected by a) CO ₂ x stage interaction and b) CO ₂ x depth interaction	98

List of Figures cont...

List of Figures cont...

Fig. No.	Figures	After page
80	Labile carbon (LBC, mg kg ⁻¹) in soil during rice growth under FACE as influenced by the main effects of a) levels of CO ₂ , b) stages of growth and c) depths of soil	99
81	Labile carbon (LBC, mg kg ⁻¹) in soil during rice growth under FACE as affected by a) CO ₂ x stage interaction and b) CO ₂ x depth interaction	99
82	Total soil carbon (TSC, g kg ⁻¹) in soil during rice growth under FACE as influenced by the main effects of a) levels of CO ₂ , b) stages of growth and c) depths of soil	100
83	Total soil carbon (TSC, g kg ⁻¹) in soil during rice growth under FACE as affected by the interaction between levels of CO ₂ and depths of soil	100
84	Microbial biomass carbon (MBC, mg kg ⁻¹) in soil during wheat growth under FACE as influenced by the main effects of a) levels of CO ₂ , b) stages of growth and c) depths of soil	101
85	Microbial biomass carbon (MBC, mg kg ⁻¹) in soil during wheat growth under FACE as affected by a) CO ₂ x stage interaction and b) CO ₂ x depth interaction	101
86	Dissolved organic carbon (DOC, mg kg ⁻¹) in soil during wheat growth under FACE as influenced by the main effects of a) levels of CO ₂ , b) stages of growth and c) depths of soil	102
87	Dissolved organic carbon (DOC, mg kg ⁻¹) in soil during wheat growth under FACE as affected by a) CO ₂ x stage interaction and b) CO ₂ x depth interaction	102
88	Carbohydrate carbon (CHC, mg kg ⁻¹) in soil during wheat growth under FACE as influenced by the main effects of a) levels of CO ₂ , b) stages of growth and c) depths of soil	103
89	Carbohydrate carbon (CHC, mg kg ⁻¹) in soil during wheat growth under FACE as affected by a) CO ₂ x stage interaction and b) CO ₂ x depth interaction	103
90	Labile carbon (LBC, mg kg ⁻¹) in soil during wheat growth under FACE as influenced by the main effects of a) levels of CO ₂ , b) stages of growth and c) depths of soil	104
91	Labile carbon (LBC, mg kg ⁻¹) in soil during wheat growth under FACE as affected by a) CO ₂ x stage interaction and b) CO ₂ x depth interaction	104
92	Total soil carbon (TSC, g kg ⁻¹) in soil during wheat growth under FACE as influenced by the main effects of a) levels of CO ₂ , b) stages of growth and c) depths of soil	104

List of Figures cont...

List of Figures cont...

Fig. No.	Figures	After page
93	Total soil carbon (TSC, g kg ⁻¹) in soil during wheat growth under FACE as affected by the interaction between levels of CO ₂ and depths of soil	104
94	Per cent increase in different carbon pools in FACE field with test crops as influenced by elevation of CO ₂	105
95	Relative increase (per cent) in different active carbon pools (averaged over all the crop growth stages) in FACE field during rice growth as influenced by elevation of CO ₂	106
96	Relative increase (per cent) in different active carbon pools (averaged over all the crop growth stages) in FACE field during wheat growth as influenced by elevation of CO ₂	106
97	Amount (g) of ambient CO ₂ - (RA) and elevated CO ₂ -grown (RE) rice residues remaining in litterbags during different days of decomposition	108
98	Carbon contents (per cent) of ambient CO ₂ - (RA) and elevated CO ₂ -grown (RE) rice residues remaining in litterbags at different days of decomposition	108
99	Nitrogen contents (per cent) of ambient CO ₂ - (RA) and elevated CO ₂ -grown (RE) rice residues remaining in litterbags at different days of decomposition	109
100	The C:N ratio of ambient CO ₂ - (RA) and elevated CO ₂ -grown (RE) rice residues remaining in litterbags at different days of decomposition	109
101	Kinetics of decomposition of ambient CO ₂ - (RA) and elevated CO ₂ - (RE) grown rice residues	109
102	Total soil organic carbon (per cent) during various stages of decomposition of ambient CO ₂ - (RA) and elevated CO ₂ -grown (RE) rice residues in litterbags placed in ambient and elevated phytotron chambers	110
103	Microbial biomass carbon (MBC, mg kg ⁻¹) in soil during decomposition of ambient CO ₂ - (RA) and elevated CO ₂ -grown (RE) rice residues in litterbags placed in ambient and elevated phytotron chambers	110
104	Ammoniacal nitrogen (kg ha ⁻¹) in soil during various stages of decomposition of ambient CO ₂ - (RA) and elevated CO ₂ -grown (RE) rice residues in litterbags placed in ambient and elevated phytotron chambers	111

List of Figures cont...

List of Figures cont...

Fig. No.	Figure	After page
105	Nitrate nitrogen (kg ha ⁻¹) in soil during various stages of decomposition of ambient CO ₂ - (RA) and elevated CO ₂ -grown (RE) rice residues in litterbags placed in ambient and elevated phytotron chambers	111
106	Amount (g) of ambient CO ₂ - (WA) and elevated CO ₂ -grown (WE) wheat residues remaining in litterbags during different days of decomposition	112
107	Carbon content (per cent) of ambient CO ₂ - (WA) and elevated CO ₂ -grown (WE) wheat residues remaining in litterbags at different days of decomposition	112
108	Nitrogen content (per cent) of ambient CO ₂ - (WA) and elevated CO ₂ -grown (WE) wheat residues remaining in litterbags at different days of decomposition	113
109	The C:N ratio of ambient CO ₂ - (WA) and elevated CO ₂ -grown (WE) wheat residues remaining in litterbags at different days of decomposition	113
110	Kinetics of decomposition of ambient CO ₂ - (WA) and elevated CO ₂ - (WE) grown wheat residues	114
111	Total soil organic carbon (per cent) during various stages of decomposition of ambient CO ₂ - (WA) and elevated CO ₂ -grown (WE) wheat residues in litterbags placed in ambient and elevated phytotron chambers	114
112	Microbial biomass carbon (mg kg ⁻¹) in soil during decomposition of ambient CO ₂ - (WA) and elevated CO ₂ -grown (WE) wheat residues in litterbags placed in ambient and elevated phytotron chambers	114
113	Ammoniacal nitrogen (kg ha ⁻¹) in soil during various stages of decomposition of ambient CO ₂ - (WA) and elevated CO ₂ -grown (WE) wheat residues in litterbags placed in ambient and elevated phytotron chambers	115
114	Nitrate nitrogen (kg ha ⁻¹) in soil during various stages of decomposition of ambient CO ₂ - (WA) and elevated CO ₂ -grown (WE) wheat residues in litterbags placed in ambient and elevated phytotron chambers	115
115	The predicted (solid line) and observed (dotted line) values of different parameters associated with the decomposition of ambient CO ₂ -grown rice (RA) residues under ambient atmospheric CO ₂ conditions	118

List of Figures cont...

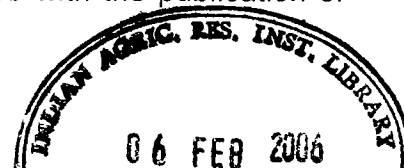
LIST OF PLATES

Plate No.	Plates	After page
1	Open Top Chambers (ambient and elevated CO ₂) used in the study with rice crop at maximum tillering stage (<i>Kharif</i> season, 2004).	40
2	Free Air Carbon dioxide Enrichment (FACE) facility with rice crop in <i>kharif</i> season, 2004.	47
3&4	Litterbags and pots with litterbags inserted into soil used in decomposition study	51
5	Pots with litter bags arranged on racks inside the phytotron chambers	51
6	Phytotron chamber (maintained at elevated CO ₂) used in the decomposition study	51
7	General growth of rice plants after flowering under elevated and ambient CO ₂	64
8	General growth of wheat plants after flowering under 1) ambient and 2) elevated CO ₂	78

1. INTRODUCTION

Faced with the fact that human activities are contributing to drastic global climate changes, the researchers in soil and plant sciences are increasingly being primed to address the problems of global proportions. Accelerating changes in the earth's environment are being driven by the growth in human populace, increasing level of resource consumption and changes in the technologies as well as socio-political organizations. The population has doubled since 1960 and tripled since 1930. While petroleum was discovered 150 years before only, human kind has already exhausted almost 40 per cent of known oil reserves that took over several hundred million years to generate (USGS, 2000). Transport alone accounts for 25 per cent of world energy. Global communication has exploded with development and urbanization has increased ten folds during twentieth century, putting forth the altered environment to the new millennium.

The well documented global changes affecting agriculture are the changes in land use and land cover, world wide decline in biodiversity, changes in atmospheric composition of gases and changes in climate. One of the major driving forces for global climate change is the relatively rapid increase in the green house gases (GHG) in the troposphere. Concerns are emerging nowadays about global climate change driven by increasing atmospheric contents of the GHGs, especially CO₂, the prime GHG with a contribution of 50 per cent to global warming. Carbon dioxide is a major green house gas that can instigate grim alterations and colossal impacts on all the four spheres (biosphere, lithosphere, atmosphere and hydrosphere) of life. Over the last two decades a new imperative has come to dominate environmental concerns with growing awareness that human activities have impact on the atmospheric concentrations of green house gases. The heat absorbing property of the GHGs linking to climate change came into sharp focus in 1999 with the publication of



the record from Vostok ice core studies (Petit *et al.*, 1999). This data, which is the most important produced by the global climate change scientific community in the twentieth century, along with very consistent measurement of atmospheric CO₂ concentration at Mauna Loa observatory in Hawaii (Keeling *et al.*, 1995) first demonstrated beyond doubt that human activities can impart direct global scale consequences for the environment. Per capita CO₂ emission from South Asia was 0.47 Tg (1995) whereas its projected value is 0.90 Tg for 2050. The total regional emission of GHG is 3 per cent of the global total, the annual growth rate being 6, 8 and 10 per cent for India, Bangladesh and Pakistan, respectively (IPCC, 2001).

In the Kyoto Protocol, most of the international community agreed to aim at reducing total GHG emissions by 2008 to 2012 to levels 5.3 per cent below those of 1990. Critics have charged that such reductions will place devastating economic burdens on industrial nations because they would be forced to reduce their energy consumption and switch to more expensive energy generation technologies. However, as recently shown by DeLeo and coworkers (2001), the costs of the proposed emission reductions will be largely offset by lowered costs related to the environmental, human health, material and agricultural damages caused by unchecked GHG emissions. Moreover soil management might play a contributing role to the economic feasibility of meeting the proposed emission reduction targets. Managing soils to increase the stocks of carbon stored as SOM can be expected to decrease the rate of increase in atmospheric CO₂. Consequential improvement in soil quality thus resulting, is of additional benefit. As the level of CO₂ rises in the atmosphere, many plants including crops respond with increased net productivity, some of which is shunted to the soil *via* increased root growth and exudations (Islam *et al.*, 1999). The resulting sequestration of C in soil organic matter might counteract, to some degree, the rise in C stored in the atmosphere as CO₂. The interplay between soil carbon and atmospheric CO₂ is one possible feedback control on global warming and is yet to be explored.

Due to increased fossil fuel combustion and deforestation, CO₂ levels have increased to 370 ppm today and will further increase to 388-399 ppm by 2010-2015 and to 463-623 ppm by around 2050/2060. Of all the carbon derived from human activity, approximately one third is accumulated in the atmosphere; one third is taken up by terrestrial biosphere, while the rest one third goes to the oceans. The largest store of C in terrestrial ecosystems is in soil which accounts for about two third of total C stored (Schimel *et al.*, 1994).

The impact of increasing CO₂ concentration on different organization levels of the ecosystem has been studied, giving major thrust on the tropospheric component of the biosphere. By their nature, answers to the questions will be complex and ^{are} likely to include feedbacks between poorly understood components of plant-soil system. Global increases in CO₂ concentration may yield primary effects on leaf and whole plant photosynthesis and C allocation, which in turn may spawn secondary consequences for root growth, fine root turnover, microbial dynamics in the soil, litter quality, residue decomposition and nutrient cycling. The potential for terrestrial ecosystems to sequester carbon from the atmosphere is governed both by their net primary production (NPP) and by their capacity for soil C storage. Examination of direct and indirect effects of elevated CO₂ on ecosystem processes occurring belowground is essential for assessing the possible degree of C sequestration. The link between the terrestrial or belowground (soil) and the biomass under the changing conditions is still to be explored. At the ecosystem scale, issues of particular interest are the complex relationships between the rise of atmospheric CO₂ and the biogeochemical cycles of the main nutrients.

The role of soil fertility in regulating the responses of plants to rising atmospheric CO₂ is important in understanding the consequences of global climate change. There is strong evidence that below ground processes ~~is~~ affected by increase in atmospheric CO₂. Several studies have shown that root growth responds disproportionately to increases in atmospheric CO₂ (Norby *et al.*, 1986, 1987, 1992; Rogers *et al.*, 1992; Johnson *et al.*, 1994; Kant, 2004). Norby and coworkers (1987) found increased root exudation from *Pinus*

echinata under elevated CO₂, and suggested that this may provide a mechanism for enhancing rhizosphere nutrient availability. Zak *et al.* (1993) reported an increase in labile C and N in soil from *Populus grandidentata* seedlings grown under elevated CO₂. On the basis of such results scientists have suggested that elevated CO₂ may create a positive feedback on soil C and N dynamics and thereby on plant growth. But the hypothesis lacks realistic evidence.

A central problem in understanding the global C cycling is the inability of the present knowledge to account for the flow of C. While sources of atmospheric CO₂ are well documented, sinks are not. An unknown sink of 2.2 Pg C/yr is often referred to as 'missing sink' (Houghton *et al.*, 1990). Below ground effects of elevated CO₂ are important and must be monitored in experiments involving CO₂ treatments with predominant cropping patterns such as Rice-Wheat cropping system in Indo-Gangetic Plains. It has been hypothesized that the surplus C is being stored in terrestrial ecosystems as a result of higher plant productivity caused by elevated atmospheric CO₂ levels (Kimball, 1983). Carbon fixed within the plant biomass ultimately enters the soil via plant residues, where it may reside for hundreds of years. Ultimately the rate and extent of turnover of organic C produced in an elevated CO₂ environment will control C storage in terrestrial ecosystems (Van Veen *et al.*, 1991).

The effects of elevated CO₂ on ecosystem processes in general and decomposition of plant litter in particular, have received little attention (Lambers, 1993). The production of below ground litter and its quality are likely to be affected by an increase in atmospheric CO₂ with subsequent changes in decomposition rates (Cotrufo & Ireson, 1995; Gorissen *et al.*, 1995; Van Ginkel *et al.*, 1996). A shift in species composition favouring the superior competitors in vegetation under elevated CO₂ may induce further changes in the litter decomposition rates of a community (O' Neill, 1994). The elevated CO₂ in the atmosphere results in increased allocation of carbon to fine roots and may thus increase the total viable rhizosphere and bulk soil microbial biomass or induce shifts in microbial and mycorrhizal community structure. Such shifts have the

potential to alter the patterns of bio-mineralisation, soil formation and nutrient pool sizes. The changes in C input to the soil could have a dramatic effect on rates of below ground processes and such effect is likely to be different under varying climatic conditions. Grass root decomposition was found to be retarded when grass was grown under elevated CO₂ (Gorissen *et al.*, 1995). In a study conducted by Ball (1991) the comparison of the rates of microbial degradation of stem material derived from wheat grown at ambient or elevated atmospheric CO₂ concentrations revealed significant differences in bio-degradability with a reduction in microbial biomass and bio-degradation of approximately 20 per cent when plant material derived from wheat grown under elevated CO₂ replaced the ambient plant material. Cotrufo and coworkers (1994) found that elevated CO₂ significantly affected some of the major litter quality parameters (trees) with lower N, higher lignin concentrations and higher ratios of C/N and lignin/N for litter derived from enriched CO₂ conditions. Litter quality parameters when examined for correlation with cumulative respiration and decomposition rates, N concentration, C/N ratio and the lignin/N ratios showed highest correlation with differences between litter types. Thus the results indicated that higher C storage would occur in soil as a consequence of changes in litter quality resulting from higher atmospheric concentrations of CO₂. The results of the experiment conducted by Torbert *et al* (1995) using cotton residues indicated that while decomposition of plant residue may not be reduced by CO₂ enrichment, N dynamics may be markedly changed. Elevated temperatures (as a result of high CO₂) may stimulate decomposition of soil organic matter and mineralization of nutrients (Stanford *et al.*, 1973). The effect of elevated temperature might be buffered if litter produced under elevated CO₂ has a higher C/N ratio and decomposes rather slowly (Cotrufo *et al.*, 1994).

Few studies have attempted to measure the effects of CO₂ enrichment on C cycling in terrestrial ecosystems. In a review by Bazzaz (1990) it was suggested that decomposition rates of plant residue from high-CO₂ environments would be slower. Experiments have started in this direction and the species dependence has been reported regarding the rates of residue

decomposition. The elevated CO₂ as well as the associated climatic factors, which have not yet been attempted comprehensively in any of the experiments, may affect the decomposition rates further. Changes in plant morphology, physiology and phyto-chemistry as a result of increasing levels of atmospheric CO₂ also will have dramatic impact on plant-microbe interactions and thus on C cycling and the potential for carbon storage in soil. As the nitrogen dynamics is interrelated with carbon cycling the impact of elevated CO₂ on nitrogen mineralization is also an interesting line of research.

To date, predictions regarding whole ecosystem responses are largely based on modeling, in which results from small-scale green house studies and laboratory incubations have been extrapolated to ecosystem scale. The short term controlled environmental studies can be complemented using the model approaches in this regard. With these ideas in background the present work was undertaken with the following objectives:

1. To study the effect of elevated CO₂ on different fractions of carbon in soil under Rice-wheat cropping system.
2. To study the effect of elevated CO₂ on kinetics of residue decomposition.
3. Testing of CERES model to predict N mineralization in soil under elevated atmospheric CO₂ conditions.

2. REVIEW OF LITERATURE

The consulted literature relevant to the current study is reviewed under the following headings:

1. Rise in atmospheric CO₂
2. Carbon dioxide enrichment technologies
3. Crop responses to elevated CO₂
4. Soil changes
5. Litter quality and decomposition under elevated CO₂
6. Modelling the responses to elevated CO₂
7. Carbon dioxide response studies in India

2.1 RISE IN ATMOSPHERIC CO₂ - Its Climatic, Biological and Ecological Effects

Global climate changes are unique research challenges to the agricultural scientists. The exponential rise in CO₂ concentration of the atmosphere is one of such important changes that effectively influence the productivity of the crop plants. The relatively rapid increase in atmospheric carbon dioxide during last 50 years is caused by profligate use of fossil fuels for energy in west (particularly North America and Europe) and by the deforestation in the third world countries (particularly South America, Southeast Asia and Indonesia). Human activities are adding CO₂ to the atmosphere at a rate roughly comparable to the natural geochemical processes that emitted or absorbed the gas.

The rise in CO₂ is more rapid than at any time in the past on geologic time scales. Measurement of CO₂ in the atmosphere, which began in Antarctica in 1957, and Mauna Loa in (Hawaii) in 1958 indicates clearly that the concentration of CO₂ in the atmosphere is increasing rapidly. Prior to

industrial revolution, the global CO₂ concentration was about 270 ppmV, which remained stagnant for 10,000 years. Mauna Loa studies observed an increase of 1.0 $\mu\text{mol mol}^{-1} \text{ yr}^{-1}$ from 1958 to 1982. The 1958 value of atmospheric CO₂ concentration was 316 $\mu\text{mol mol}^{-1}$ (Keeling *et al.*, 1995) and in 1995-2000, it was recorded as high as 360 $\mu\text{mol mol}^{-1}$ (Collette, 1995) and today it is 372 $\mu\text{mol mol}^{-1}$ (Upriety *et al.*, 2004), which is approximately 33 per cent more, since the beginning of the industrial revolution. An increase at the rate of 1.5-1.8 $\mu\text{mol mol}^{-1} \text{ yr}^{-1}$ has been reported (Keeling *et al.*, 1995) and is likely to be doubled by the end of the 21st century (Houghton *et al.*, 1996).

The drastic increase in human population since the pre industrial revolution increased the concentration of CO₂ due to large-scale use of fossil fuels, deforestation, industrialization and urbanization. Gifford (1994) showed that burning of fossil fuel puts 5.8 - 6.2 Gt C year⁻¹ into the atmosphere and tropical deforestation adds another 1.5 - 3.0 Gt C year⁻¹ accumulating about 8.0 Gt C year⁻¹ with atmospheric level. Of this 4.7 Gt C is being absorbed by the oceanic and terrestrial biota per year and 3.3 Gt C year⁻¹ remains in the atmosphere leading to the rise in its concentration (Tans and Bakwin, 1995). Among the countries, the major contribution of the total CO₂ emissions of the world is by USA (41%), followed by Germany (22%) and Japan (21%). India contributes only 2 per cent of the total CO₂ emissions of the world (WB, 2001).

2.1.1 Importance of CO₂-climatic effect

The influence of greenhouse gases (GHGs) on climate can be broadly dealt with using the concept of radiative forcing. Radiative forcing is a measure of the influence expressed in terms of its capacity to alter the balance of incoming and outgoing energy in the earth atmosphere system. It is an index of the importance of a factor in potential climate change mechanism. The total radiative forcing due to increase of the well-mixed GHGs from 1750 to 2000 is estimated to be 2.43 Wm⁻². Out of this, respective contributions from different GHGs are: 1.46 Wm⁻² from CO₂; 0.48 Wm⁻² from CH₄; 0.34 Wm⁻² from the halocarbons; and 0.15 Wm⁻² from N₂O. The increase in CO₂ concentration in the atmosphere caused global warming by absorbing

long wave heat radiations from earth's surface, often termed as 'climatic effect'.

The cumulative value of surface temperature change without such feedback during the period 1850 -1980 was 0.56 °C of which Carbon dioxide increase contributed an increase of 0.4 °C and the contributions from other trace gases were approximately 0.16 °C. Several theoretical models have predicted that near global temperature will increase 3-4 °C with doubling of CO₂ concentration (IPCC, 2001). Long-term temperature records have concluded that global temperature has increased about 0.5 °C about the last 100 years (Hurrell, 1998). Warmer spring summer air temperature might be beneficial to crop yield at north (Jones *et al.*, 1985). However, more recent experiments indicate that the temperature rise will be less than 0.26 °C for a doubling of CO₂ concentration in temperate latitude where length of growing season could increase (Bazzaz, 1990). However, the increased temperature may have negative effect in Mediterranean type of environment, where high summer temperature and water stress already limiting production of crops.

2.1.2 Importance of CO₂ – biological effect

Plants have been directly affected by rising atmospheric CO₂ as it serves as a main substrate of the photosynthetic carbon assimilation. There is concomitant decline in photorespiratory activity and alterations in stomatal behaviour (biological effect). The C₃ plants (wheat, rice, oilseed, pulses *etc.*) respond to elevated CO₂ more since it reduces the oxygenase activity of RuBP carboxylase-oxygenase enzyme in plants. The photosynthetic enzyme in C₄ plants is phospho-enol-pyruvate carboxylase, which is not competitively inhibited by O₂ and thus the system is already CO₂ saturated. Hence C₄ plants (sorghum, maize, sugarcane *etc.*) show little or no photosynthetic response to elevated CO₂. The differing responses of C₃ and C₄ species to CO₂ might affect the competitiveness of weeds. The C₃ weeds may become more problematic in C₄ crops, whereas C₃ crops may get advantage over C₄ weeds. This can have great impact in the complexion of agro-ecosystems (Drake, 1992).

2.1.3 Importance of CO₂-ecological effect

Increasing CO₂ in the atmosphere can enhance plant growth through carbon fertilization, thus removing some of the excess CO₂ from atmosphere. For perennial plants like trees part of this carbon might be sequestered for decades or centuries. All types of plants can contribute organic carbon into soil organic matter through litter-fall and root decomposition. This in turn might alter the carbon dynamics and associated mineralisation processes taking place in the soil ecosystem. Such changes, if continued for a long term, might accumulate in some stabilized fractions with turnover on time scales of centuries or even millennia. This carbon sequestration would tend to offset global climate change to a certain extent (Powlson, 2005). Relationships of these three major changes and the consequence on C cycle are expressed diagrammatically in figure 1. All these changes in the agro ecosystems are researchable issues of high priority. The need of understanding ecosystem processes under elevated atmospheric CO₂ led to the development of various CO₂ enrichment technologies.

2.2 CARBON DIOXIDE ENRICHMENT TECHNOLOGIES

2.2.1 Initial phase of carbondioxide enrichment studies

The credit for the first recorded observation of the effect of CO₂ on plant growth is attributed to de Sassure who noted that pea plants grew faster when exposed to an atmosphere enriched with CO₂. The first description of the greenhouse effect of CO₂ was given by John Tindal. Swedish Nobel prizewinner Svante Arrhenius and American geologist T.C. Chamberlin first published an account on greenhouse effect (Uprety *et al.*, 2000). Lundegardh carried out the first CO₂ experiment in the field in 1920-23 on sugarbeet and oat. He observed 16 per cent increase in sugarbeet root production with 15 per cent increase in CO₂ concentration, whereas oat production was 30 per cent more for doubling of CO₂ concentration. By 1961, about 400 acres of greenhouse crops were being grown with CO₂ enrichment in the Netherlands.

Most of the researches on plant responses to high CO₂ concentration have been conducted in the past under laboratory, greenhouse or controlled

field conditions (Bazzaz and Garbutt, 1988). With the development of temperature control in greenhouse, the studies on interactive effect of CO₂ and temperature became possible (Mitchell *et al.*, 1995). Agricultural scientists have used controlled environments and field based facilities such as leaf cuvetts, whole-plant growth chambers *etc.* to study the crop responses to individual factors such as radiation, temperature, humidity and water availability. Technologies earlier used were based on single component approach, and have been successfully applied to study the responses of plant to a single factor such as increased CO₂. Although this single component approach is highly effective way of exploring how one atmospheric factor might influence crops, in practice, several interactions will influence the actual response. Thus innovative approaches have been developed for conducting long-term experiments to investigate the impact of rising atmospheric CO₂ and temperature interactions on crop plants.

Nowadays there are precisely controlled closed systems such as growth cabinets, phytotron, growth chambers *etc.* and open field exposure systems such as open top chambers (OTC) and free air carbon dioxide enrichment (FACE) frequently used for CO₂ enrichment studies. The field exposure systems are moderately more expensive and less precise than closed systems (Allen *et al.*, 1992). Each of these research systems has its advantages as well as disadvantages. New methods and facilities have been devised and non-interfering field exposure techniques are being developed and improved for exposure of larger area to elevated CO₂. In the current decade, there have been new approaches for the development of CO₂ and temperature enrichment system known as FATE (Free Air Temperature Enrichment) technology. In the current study, OTCs and FACE technologies were used for studying the crop responses to the CO₂ enrichment. The decomposition studies were done in closed phytotron chambers.

2.2.2 Open top chambers (OTC)

To characterize the responses of crop plants, a CO₂ enrichment technique, especially that do not significantly modify microclimate was developed and improved for exposures of crops to elevated CO₂ under near

natural conditions. OTCs as described by Heagal *et al.* (1973) have been extensively used as plant exposure units both in air pollution and in CO₂ response studies in the field. These systems have been used to expose potted plants, annual crops and trees to a variety of air pollutants and CO₂. They are currently in use at a number of laboratories in North America, Europe and South-Asian countries. Hardy and Hevelka (1975) first used a square wall open top enclosure to expose soybean plants to atmosphere enriched with CO₂ for the purpose of studying the effect on photosynthetic production and symbiotic nitrogen fixation. Rogers and co-workers (1983) adapted the basic cylindrical open top chamber system to generate large-scale CO₂ test atmospheres in the field. Nakayama and Kimball (1988) used a square wall open top chamber with 0.2 m diameter perforated polythene rolled in cotton. Drake *et al.* (1989) developed an OTC system for CO₂ enrichment of salt marsh vegetation that re-circulated part of input air. Uprety (1998) designed and developed OTC for South Asian climatic conditions. These chambers are being used by South Asian research network for multi-country, multi-disciplinary CO₂ response experiments.

OTC is one of the most widely used techniques for studying the responses of crops and crop ecosystems to the elevated CO₂. The microenvironment of typical open top chamber was characterized as having 5 to 7 per cent less solar radiation, higher humidity and lower wind speed compared to open field. This particular change in the microenvironment is nullified through the use of OTCs maintained at ambient CO₂ concentration as control. The technical description regarding working of OTCs is given in the 'Materials and methods' section.

2.2.3 Free Air Carbon dioxide Enrichment (FACE) Technology

Besides open top chambers, a new advanced technique known as FACE has been developed and used all over the world. FACE provides an approach for enriching relatively larger areas of vegetation with CO₂ for extended period of time. It involves less cost per unit experimental area than any other known techniques. This system has been engineered and developed by Brookhaven National Laboratory, New York, USA. The FACE

system is an example of the application of modern technology to field experimentation to enable detailed observations and experiments with crop and ecological systems that previously were beyond the reach of our scientific intelligence. The FACE system could open new opportunity to address questions in the frontier areas of agricultural sciences ranging from molecular biology, plant community dynamics to global carbon balance.

The FACE system is defined as a circular array of independently valved vent pipes from which CO₂ is injected into treatment plot through a mass-flow controller regulated by an algorithm that account for wind direction, wind velocity and running average gas concentration measured in the centre of the treatment plots. It consists of four subsystems.

- a) CO₂ storage and vaporization system
- b) CO₂ flow and distribution system
- c) CO₂ regulation and control system
- d) Performance monitoring and data logging system

There are different types of FACE systems developed in recent years, which include, Arizona FACE system with vertical vent pipes. It is around 22 m in diameter and is located in Maricopa, Arizona, USA (Hendrey, 1993). A mini FACE system has been developed by the Institute of Agro-meteorology and Environmental Analysis, Firenze, Italy. In this case the FACE ring is less than 2 m in diameter and the system is portable. It was used in Europe during mid-nineties. Mid-FACE is another type of FACE technology that was developed by Japanese scientists under the leadership of Kobayashi at the National Institute of Agro-environmental Sciences, Ibaraki, Japan. It is octagonal in shape with a vertical FACE ring (Upreti *et al.*, 2000).

The present experiment was done in the South Asian mid-FACE designed and developed at Indian Agricultural Research Institute, New Delhi (Upreti *et al.*, 2000). The FACE ring in this case is of 8 m diameter, octagon-shaped and is having horizontal vent pipes. This facility is also being used by the South Asian countries viz., Bangladesh, Nepal, Pakistan and Sri Lanka at

Indian Agricultural Research Institute, New Delhi for analyzing the responses of crops and the ecological C balance.

Advantages of FACE technology over OTC

- a) More Stable control of CO₂ concentration
- b) Exposure to larger plot area
- c) Sufficient plant material for extensive sampling
- d) Less cost investment compared to other systems
- e) Low cost per sample unit
- f) Low cost per sample investigator (multidisciplinary approach)

2.3 CROP RESPONSES TO ELEVATED CO₂

Considerable basic physiological information is now offered from a large number of studies showing that increases in ambient CO₂ have varied and profound consequences on plant growth. These effects of elevated CO₂ can be experimentally demonstrated with concentration increases in the upper end of the range expected to occur by the middle of next century. The major effects are on photosynthesis and respiration, and thereby on growth (the accumulation of dry matter). There are additional effects of increased atmospheric CO₂ on plant development, crop quality and water use efficiency.

2.3.1 Photosynthesis, respiration and growth

In general, as photosynthesis is the net accumulation of carbohydrates formed by the uptake of CO₂, an increase in its concentration results in increased rate of photosynthesis. In general, a doubling of CO₂ increased the photosynthetic rate by 30 per cent; depending on other environmental conditions (Kimball, 1986). The balance between the photosynthetic gain and loss of carbohydrate from plants by respiration is the resultant growth. Unfortunately the response of respiration to CO₂ has been little studied and there are suggestions that respiration could be lower rather than higher owing to a changed carbohydrate status. This process may underlie in some of the unexpectedly high responses observed in growth as a response to increased CO₂. Within a single species responsiveness differ among cultivars and

genotypes. Such differences offer possibility of breeding to harvest optimum advantage under increased CO₂.

Interactions with other environmental conditions are critical in determining the net effect of increased CO₂. In particular, it has been demonstrated that in adverse conditions (e.g. nutrient limitation, water shortage, salinity, cool temperatures and air pollution) the relative effect of increased CO₂ is larger over ambient conditions (Morison, 1988). Plants exhibit varied changes in photosynthetic rate in response to the elevation of atmospheric CO₂ and the response largely depends on whether they are of C₃ or C₄ nature.

2.3.1.1 C₃ and C₄ plants

There are two groups of plants, differing in their fundamental carbon fixation biochemistry- the C₃ and C₄ types. Most crops grown in cool, temperate or moist habitats are C₃ plants, so are all the trees. The C₃ group therefore accounts for the majority of the world's plant biomass. Although C₄ crops account for only about one-fifth of the world's food production, they are important sources of food particularly in the tropical regions. Maize, an important C₄ crop, alone accounts for 14 per cent of world food. Moreover, many pasture and forage grasses grown worldwide are C₄, including important prairie grasses in the US as well as in the subtropics and tropics. It is widely accepted that the response of growth to elevated CO₂ in C₃ plants (e.g. wheat, rice, barley, root crops, legumes) is larger than that of C₄ plants (e.g. maize, sorghum, millets, sugarcane).

It has been estimated that the average effect of doubling atmospheric CO₂ concentration on wheat grain causes an increase of 35 per cent yield while that on maize has not been adequately quantified (Cure, 1985). A third set of biochemically defined group of plants occurring substantially in the arid zone is that with CAM metabolism (Crassulacean Acid Metabolism), which includes several plants in the cactus family, the *Crassulaceae* and desert succulents. In this group the species of major commercial importance are sisal and pineapple. These plants will show little or no response to increased CO₂.

It is well known that elevated CO₂ stimulates photosynthesis. The main uncertainties are regarding the degree of stimulation for each species under a set of environmental conditions. Also equally important is to study whether or not the plants acclimate to the higher CO₂ by altering the biochemical makeup of their photosynthetic apparatus, so that photosynthetic rate at high CO₂ ultimately stabilizes to that observed at today's ambient CO₂. The biochemical and molecular basis for such photosynthetic acclimation have been reviewed by Moore and co-workers (1999). For upper leaves the CO₂-induced responses in photosynthesis ranged from about 25 to 45 per cent under ample water and high nitrogen for wheat, ryegrass, and cotton, all of which are C₃ photosynthetic crops. At low N the values were somewhat lower for wheat, but surprisingly, they were higher for ryegrass. For sorghum, the stimulation was much less, only about 9 per cent, which is as expected for a C₄ crop. However, under water stress sorghum had a larger response of about 23 per cent. This was probably so due to the effect of elevated CO₂ on plant water relations than a direct stimulation of photosynthesis (Brooks *et al.*, 2001). Wheatears responded somewhat more than the upper leaves (Wechsung *et al.*, 1999 and 2000). Tropical plants showed alterations in morphology and biomass distribution due to growth in an elevated CO₂ environment. Upreti *et al.* (2003) observed an increase in plant height and tillering under elevated CO₂ concentration in rice cultivars. The alterations in photosynthetic processes is reflected as such in the yield of those crops.

2.3.2 Agricultural yield

Because of the economic importance, there have been numerous observations over the past century of the effects of elevated CO₂ on the yield of agricultural crops, especially greenhouse crops (Kimball, 1986; Lawlor and Mitchell, 1991; Susanna Marchi *et al.*, 2004). However, with impending global transformation and the need to secure food supplies for the future, several elevated CO₂ experiments have been concentrated on open-field agricultural crops. The average biomass increases due to elevation of CO₂ for C₃ grasses were about 12 per cent at ample N and ample water, 3 per cent under low N, and 14 per cent under low water (Pinter *et al.*, 1997b). Baker and associates

(1990) reported that rice plants when exposed to elevated CO₂ increased the total shoot biomass, root biomass and final grain yields. The harvest index of the rice crop also showed an increase at elevated CO₂. According to Ziska *et al.* (1997) and Moya *et al.* (1998), the additional tillers produced in rice increased the number of panicles leading to an increase in grain yield ranging from 5 to 60 per cent. Generally speaking, the wheat and rice yield increased by an average of 12 per cent as a result of elevation of atmospheric CO₂ at ample N and water. Under very high N, average rice yields increased on an average by 11 per cent; while at low N, both wheat and rice yields were stimulated by 7 per cent in response to elevated CO₂. The latter figure is considerably higher compared to the average 3 per cent increase for shoot biomass. When water was limiting, wheat yields increased by 23 per cent, which was significantly greater than the biomass stimulation (14%). The harvest index was consequently increased by elevated CO₂ under dry condition (Kobayashi *et al.*, 2001). Upreti *et al.* (2003) also showed an increase in rice grain yield at elevated CO₂ condition which was mainly attributed to increased tillering, increased number of panicle per plant and an increased grain mass.

Regarding the case of the C₄ grass, sorghum, there was a small average negative response (-5%) under ample water, but variability was high. In contrast, at low water sorghum yielded about 25 per cent more grain under CO₂ enrichment compared to ambient, which was probably due to the high CO₂-induced partial stomatal closure (Ottman *et al.*, 2001), which enabled the elevated CO₂-grown plants to maintain photosynthesis and grow longer into each drought cycle. Tuber yields from potato, a C₃ crop, increased by 28 per cent due to elevation of CO₂, which stands in marked contrast to the average 21 per cent decrease in biomass of the shoots (Miglietta *et al.*, 1998). The latter appears related to effects of elevated CO₂ on the onset of senescence (Bindi *et al.*, 1999). Nevertheless, such a marked difference in response between shoots and tubers represents a major reallocation of resources for that plant under high CO₂ to improve harvest index. The boll (seed + lint) yields of woody perennial cotton were increased by about 40 per cent due to increase in atmospheric CO₂ under both ample and low water conditions

(Mauney *et al.*, 1994). Further examination of the lint fiber portion of the yield indicated that its production was increased even more, by about 54 per cent (Pinter *et al.*, 1996). Likewise, the berry yields from woody perennial grape were stimulated by about 28 per cent. All of these yield-stimulations are slightly higher than the mean biomass stimulations and therefore represent slight improvements in harvest index.

Rogers *et al.* (1986) reported an increase in dry matter accumulation in soybean by about 78.1 per cent at $700 \mu\text{mol mol}^{-1} \text{CO}_2$ compared to $334 \mu\text{mol mol}^{-1} \text{CO}_2$. Studies in cotton (Idso *et al.*, 1987) at elevated CO_2 conditions showed that the cotton biomass increased by 82 per cent and at the same time the grain yield was increased by 87 per cent. Polle *et al.* (2001) reported an increase in whole plant biomass and stem diameter in holm oak (*Quercus ilex* L.) seedlings under elevated CO_2 condition.

Processes involved in plant growth are affected by both temperature and CO_2 and their potential interactions (Centritto *et al.*, 1999). The warming effect, acting cumulatively over long periods of time, may significantly affect the rates of both ontogenetic development and growth in leaf area and biomass (Pinter *et al.*, 1996). Warmer temperature increases the rate of ontogenetic development in determinate crops like wheat and result in substantial shortening of the growth period; which further shortens the duration of carbon fixation and biomass accumulation to seed set (Morison 1996).

2.3.3 Biomass accumulation

2.3.3.1 Shoots

Most of the chamber studies of the effects of elevated CO_2 on plants have reported the response of shoot biomass. Kimball (1986) assembled and analyzed 94 observations related to the effects of elevated CO_2 on biomass, and obtained an average increase of 21 per cent, which is within the error bar range of the mean of all the C_3 plants from different experiments ($17 \pm 3\%$). Likewise, Cure (1985) and Cure along with Acock (1986) conducted a literature survey and tabulated the results of doubling the CO_2 on the

response of 10 major agricultural crops. Scaling to 550 ppm, they reported biomass stimulations of 16, 15, 5, 46, and -8 per cent, respectively, for wheat, rice, sorghum, cotton, and potato for conditions of ample water and nutrients. Poorter (1993) computed the biomass response to elevated CO₂ of about 125 observations in the literature, and he grouped the results according to several functional group categories. Scaled to 550 ppm, he found the stimulation for both C₃ herbaceous and woody plants to be around 22 per cent and that for C₄ herbs about 11 per cent. Species categorized as C₃ N-fixers were stimulated by about 25 per cent, same as that of legumes observed in the elevated CO₂ experiments (ignoring lucerne with ineffective *Rhizohium*). He also separated the species between crops and wild, finding that crop species were stimulated by 29 per cent while wild species were stimulated only by 17 per cent. He speculated that the higher crop response might be because of the fast growing nature of crop species. Later he divided the wild species into fast, intermediate, and slow growing, and the obtained CO₂ induced stimulations were 27, 19, and 12 per cent, respectively. This suggested that fast-growing wild species were nearly as responsive as crop species to elevated CO₂.

By far the largest number of reports from elevated CO₂ experiments has been regarding the response of aboveground biomass. The C₃ grasses at ample water and nitrogen recorded mean biomass response of 11.5 per cent at elevated CO₂ (Daepp *et al.*, 2001). At very high N, the growth response of the C₃ grasses was vigorous, about 19 per cent, while low N produced a mean response of only 3 per cent increase. Under water stress, response of C₃ crops to elevated CO₂ (about a 14% increase) was larger than the corresponding response (about 8%) at ample water (Pinter *et al.*, 1997a). Large increases in shoot biomass due to elevation of CO₂ have been observed also for the woody perennials (cotton and grape), with a mean increase of about 32 per cent (scaled to 550ppm) at ample water and nutrients (Mauney *et al.*, 1992, Bindi *et al.*, 1995).

In the review of Cure (1985) and Cure and Acock (1986) they reported a decrease (8%) for the aboveground biomass of potato (scaled to 550ppm).

Elevated CO₂ caused a mean decrease of about 21 per cent in aboveground biomass of potato. In another study, which was ascribed to the apparent acceleration of senescence in elevated CO₂ (Bindi *et al.*, 1999). Occurrence of earlier senescence probably shortened the time for biomass accumulation and hastened the translocation of material from the aboveground parts to the tubers below (Mauney *et al.*, 1994).

Various CO₂ enrichment technologies also caused variation in magnitude of the response of crops to elevated CO₂. Kimball and co-workers (1997) have made the most direct comparisons of the shoot biomass response to elevated CO₂ between plants grown in FACE and Open Top Chambers. They grew cotton in OTCs for five seasons and later with FACE for three seasons. Although not done simultaneously, the experiments were conducted in the same climate using similar cultural techniques by teams with several of the same scientists. They found a mean increase in shoot biomass of about 35 per cent in FACE experiments (Mauney *et al.*, 1992, 1994) and of about 39 per cent in OTCs (scaled to 550 ppm), which were not quite significantly different. They also pointed out that although the relative responses to CO₂ were similar, the absolute growth rates were typically 30 per cent higher inside the OTCs compared to outside under well-watered conditions. They also reported another experiment with wheat in 1992-1993, when OTCs were operated simultaneously in the same field as a FACE experiment. In that case, both the relative response of aboveground biomass to CO₂ and the absolute growth rates were nearly identical under both FACE and OTC.

2.3.3.2 Roots

Raising the concentration of atmospheric CO₂ often results in dramatic increases in root growth. Root dry weight has been found to augment under elevated atmospheric CO₂ in most investigations regardless of species or study conditions (Rogers *et al.*, 1994; Kimball, 1995). In many instances roots exhibited the greatest relative dry weight gain among plant organs under high CO₂ (Hocking and Meyer, 1991; Imai and Murata, 1976; Imai *et al.*, 1985; Norby *et al.*, 1992). A majority of studies have also found that elevated CO₂

resulted in more and/or longer plant roots or faster root growth, possibly leading to increased penetration of the soil profile (Baker *et al.*, 1990; Chaudhuri *et al.*, 1990) and/or spread (Idso and Kimball, 1991).

Average root growth of C₃ grasses in the elevated CO₂ experiments was stimulated by about 47 per cent by elevated CO₂ under conditions of ample water and nutrients, which is substantially more than the stimulation (12%) for shoots (Kim *et al.*, 2001, Hebsein *et al.*, 1997). Root biomass was also increased by about 39 per cent under low N compared to only about 3 per cent for shoots. There was only one report under low water, and for that case, wheat root growth was stimulated by about 23 per cent, compared to 14 per cent stimulation for shoots (Hebsein *et al.*, 1997). Thus, there were substantial evidences of increases in the root: shoot ratio of the C₃ grasses due to elevation of CO₂ under all types of conditions.

The root growth of C₃ legumes (clover) was stimulated by about 25 per cent due to elevated CO₂ under ample N, which was nearly the same as that of the shoots (24%). When N was low, the root increase averaged to 21 per cent, which is a little less than the 26 per cent increase for the shoots (Hebsein *et al.*, 1997). Thus, CO₂ induced stimulation of shoots and roots were almost of the same order under both limited and ample N, producing little effect on the root: shoot ratio of the C₃ legumes. In case of woody perennial cotton, tap and fine root biomass were stimulated on the average by 78 and 52 per cent, respectively; although variability was high. This was more than the average 32% increase for woody perennial shoots. Hence, the root: shoot ratio also increased in this case (Kimball *et al.*, 2002).

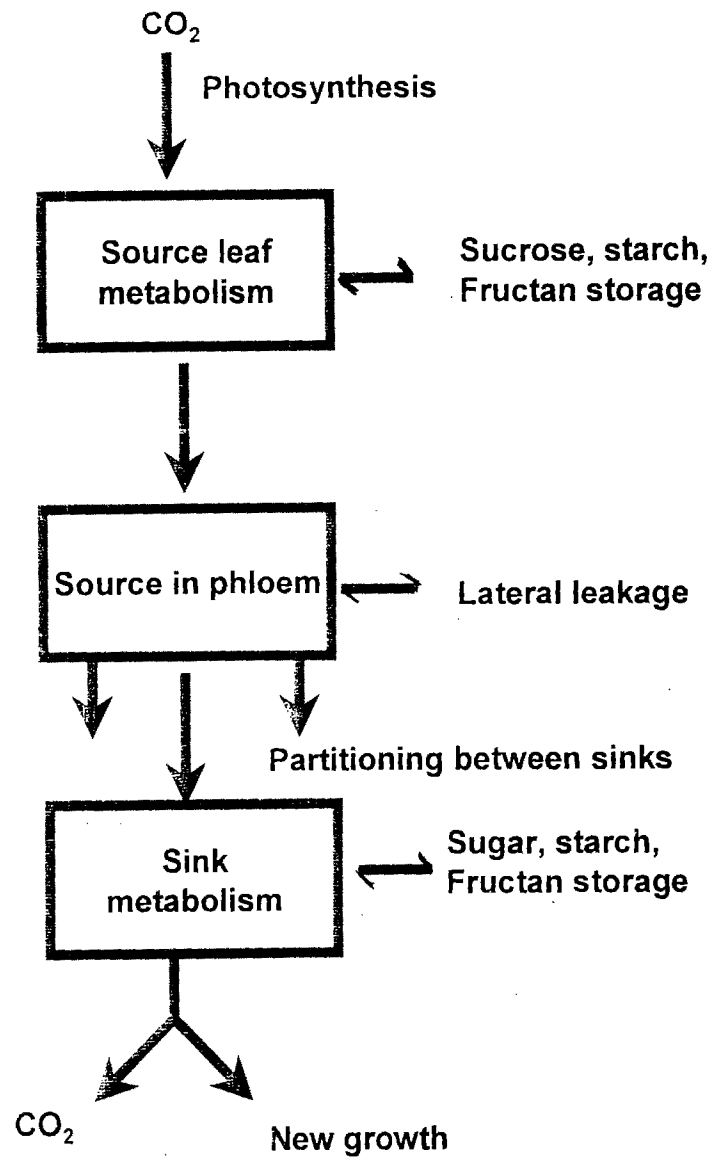
Just as there have been relatively few observations of the effects of elevated CO₂ on root growth, so there have been few reviews of these data. Rogers and co-workers (1996) also reviewed the influence of elevated CO₂ on the root: shoot ratios of agricultural crops. Inconsistency was found to be high with about 60 per cent of the observations showing an increase, 3 per cent no change, and 37 per cent a decrease. Grouping by type of crop, they calculated relative changes in the root: shoot ratio of -6 per cent for fiber crops, + 16 per cent for fruit, +6 per cent for C₃ grains, +4 per cent for C₄

and limited-soil N, which is about half the reduction of the C₃ grasses (Zanetti *et al.*, 1996). The N concentration of wheat grain was measured by Kimball and co-workers (2001), who found that the elevated CO₂ treatment caused a mean reduction of about 3 per cent under ample soil N and water, 4 per cent under low water, and 9 per cent under low soil N. Cotrufo and co-workers (1998) did an extensive examination of nearly 400 literature regarding the effects of elevated CO₂ on the nitrogen concentrations of plant tissues. On an average, the N concentration of C₃ plants was reduced by 16 per cent due to elevated CO₂ compared to only 7 per cent reduction for both C₄ and N fixing plants. The concentrations in leaves and shoots as a whole were reduced more than those of fine roots (about -16% compared to -7%). The concentration in green leaves was reduced more than that of leaf litter (-16% compared to - 7%).

2.3.5 Carbon partitioning

While photosynthesis determines the amount of substrate available for plant growth; carbon partitioning determines both the efficiency with which substrate is used and the extent of its productive investment. Some of the partial processes of C partitioning are shown in Fig. 2. A notable feature of this figure is that since there are a number of branch points (such as storage *versus* phloem loading in source leaves), it is unlikely that a change in anyone part of the system will have a simple effect on the other parts. It is also important to understand the central role of sucrose, which is the primary product of source, substrate of sink metabolism and the most abundant compound moving between them. Models of global climate change predict a future doubling of the atmospheric CO₂ concentration over the next 100 years (Houghton *et al.*, 1990). Such CO₂ enrichment can enhance the growth and yield of many C₃ plants (Kimball, 1983; Cure & Acock, 1986; Kimball and Idso, 1983), depending upon species, growth stage, nutrient status and length of exposure to elevated CO₂. In general, C₃ plants grown under elevated CO₂ show an initial increase in net photosynthesis due to suppression of photo respiratory carbon metabolism leading to an increase in biomass production (Gifford, 1982). In contrast, presumably due to the CO₂-concentrating

**Fig. 2 Schematic representation of carbon partitioning showing major processes
(Farrar and Williams, 1991)**



processes already present within the leaves of C_4 plants, these are relatively unresponsive to elevated CO_2 in terms of biomass accumulation and carbohydrate partitioning (Ford & Thorne, 1967; Cure and Acock, 1986). However, the increase in rates of carbon fixation observed for C_3 plants may not be maintained in the long-term (Chang, 1975; Porter and Grodzinski, 1984) and the final yield of the CO_2 enriched crop plants may not reflect the initial photosynthetic response (Neales & Nicholls, 1978). To understand such limitations on yield one must first understand the nature and limitation of assimilate partitioning. It is unlikely that plants sense CO_2 directly in a way related to carbon partitioning, but rather the effects of high CO_2 will be a consequence of increased photosynthesis and carbohydrate production (Mott, 1990; Paterson *et al.*, 1996). Carbon allocation is of critical importance to all plants and it has been suggested that differences in carbon allocation leads to the wide diversity of flora that inhabit Earth's biomes (Schulze, 1983). For crop plants, genetic improvement of yield has come mainly through selection for better carbon partitioning and it appears to be the most promising path for continued crop increases (Daie, 1985).

Studies with ^{14}C indicated the rapid belowground transfer of assimilates with typically 50 per cent translocated in young cereal plants of which 50 per cent is respired; while exudation /rhizodeposition is generally less than 5 per cent of the fixed carbon. Ratio of root:total plant mass decreases through the season and is affected by soil and atmospheric conditions. Limited water availability increased the allocation of ^{13}C to roots of wheat grown in columns so that at booting 0.38 of shoot C (ignoring shoot respiration) was belowground compared to 0.31 in well-watered plants. Elevated CO_2 (700 ppm CO_2) increased the proportion of root:total plant mass by 55 per cent compared with normal concentration (Gregory *et al.*, 1997)

2.4 SOIL CHANGES

2.4.1 Soil biota

Ecosystem processes that are mediated by soil biota are constrained by energy and C input to the soil. This input is likely to increase as CO_2 concentrations in the atmosphere rise, either through increased root

production or exudation, or through increased aboveground production and litter fall. The magnitude of changes in quality or quantity of C input with rising CO₂ will determine whether soil biota would represent a significant constraint to ecosystem functioning in a changing climate. We do not know if present constraints exerted by soil biota will gain importance as atmospheric CO₂ rises. Soil organisms vary in their sensitivity to changes in C input and in their impact on ecosystem processes. We need to identify which biotic groups regulate these processes, assess the importance of species diversity and functional redundancy in regulation, and determine the scales over which soil processes operate.

As the quantity and quality of plant material entering the soil are altered by the increasing atmospheric CO₂ concentration, the probability exists that microorganisms in the soil will be affected also, and so will be the rates of many soil processes mediated by these microorganisms. A variety of observations have been made in the FACE and OTC experiments on aspects of soil microbiology. Diaz and associates (1993) suggested that the increased carbon released by plants under elevated CO₂ would lead to increased microbial growth and nutrient immobilization resulting in limitation of further plant responses to elevated CO₂. However, Zak and co-workers (1993) reported that increased carbon input would stimulate microbial activity and turnover enhancing N cycling and availability. Despite the recognized importance of the soil microbial community in nutrient cycling and storage, relatively little is known about the effects of elevated CO₂ on rhizodeposition (van Veen *et al.*, 1991) or the rhizosphere microbial composition and activity (Rogers *et al.*, 1994; Zak *et al.*, 2000).

Schortemeyer *et al.* (1996) measured several microbiological parameters during the second year of the Swiss FACE Project. They were unable to detect any effect of the elevated CO₂ treatment on microbial biomass carbon or on numbers of autotrophic NH₄⁺ oxidizers in the rhizosphere under either ryegrass or clover. They also measured the numbers of *Rhizobium leguminosarum* in rhizosphere soil and found no FACE effects under ryegrass, which would be expected for a non-legume. Four years later

Marilley *et al.* (1999) measured the population numbers of heterotrophic bacteria in the soil under both ryegrass and clover. Their data provided evidence for a CO₂-induced increase in bacterial numbers in the soil that adhered to the roots at sampling (rhizosphere soil) but not in the bulk soil nor on the washed roots (rhizoplane-endorhizosphere). In contrast, Sowerby and co-workers (2000) found a 27 per cent increase in microbial biomass N in the bulk soil just after removing ryegrass plants which were exposed to ambient and twice-ambient CO₂ concentrations in open-top chambers in the field from 1989 to 1992. Wood and co-workers (1994) found high variability in the rates of N mineralization in incubated soil samples from the 1991 FACE cotton experiment, and no significant effects of elevated CO₂ were detectable. In the same experiment, Runion *et al.* (1994) found no difference between the population numbers of nematodes in the soil between elevated or ambient CO₂ treatments. A larger response was observed by Rillig and co-workers (2001) who measured the lengths of arbuscular mycorrhizal fungi hyphae in soil samples following the 1998 FACE sorghum experiment. They found 109 and 267 per cent increases due to elevated CO₂ under ample and low water supplies, respectively.

However the most interesting data are probably those of Montealegre and co-workers (2000), who showed that from 1993 through 1996 in the Swiss FACE experiment there was a qualitative change in the strains of *Rhizobium* that occupied the nodules of their white clover. In 1996 they isolated several strains of the bacteria and found shifts in the "fingerprints" of the microbial DNA. They conducted an ancillary experiment whereby strains from elevated CO₂-grown plants were inoculated together with strains from the ambient-grown plants on clover seeds, which were then grown in growth chambers at 350 or 600 ppm CO₂. In five out of six cases, the strains from the FACE plots had a higher nodule occupancy share in the plants growing at high CO₂ compared to their share at normal CO₂. The higher occupancy rates indicated that those high-CO₂ selected strains had gained a competitive advantage when inoculated on the plants growing at high CO₂. This indicates that natural selection occurred in the soil under the elevated CO₂ to favour strains better adapted to the high-CO₂ regime.

Mycorrhizal responses

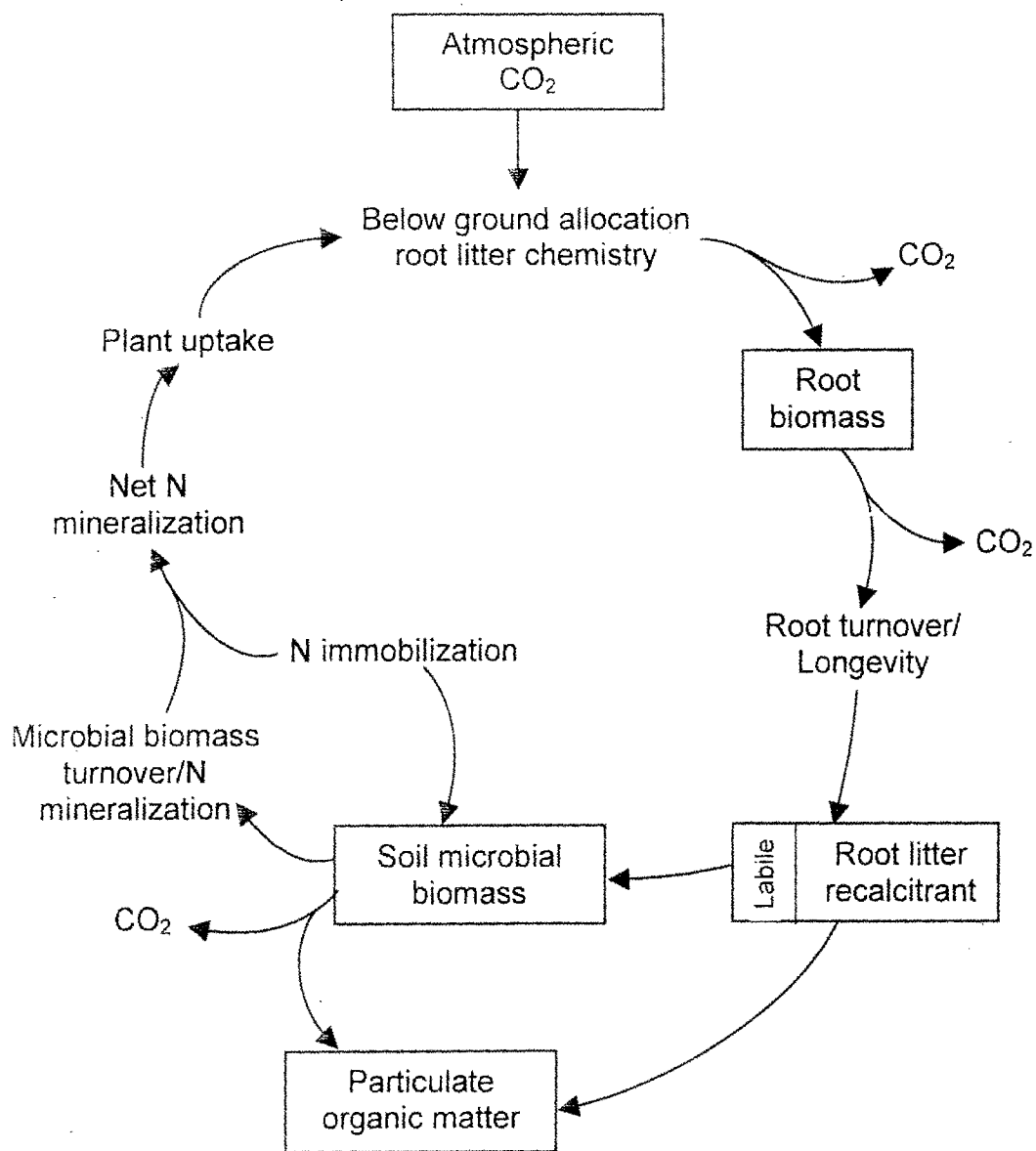
The concept of mycorrhizal benefit to host plant nutrient uptake is now generally accepted. Both Luxmoore (1981) and the Athens working group (Lamborg *et al.*, 1983) considered this symbiosis to be key to nutrient acquisition in an enriched CO₂ world. Most plant species are colonized by either ectomycorrhizal (ECM) or vesicular-arbuscular mycorrhizal (VAM) fungi. These two groups differ in their morphology, physiology, and host associations; and these differences may dictate the extent of their response to elevated CO₂. ECM fungi invest considerable plant produced C in specialized structures (mantles, fruiting bodies, rhizomorphs, and extensive extraradical mycelium). This demand for C may equate to heightened responsiveness (compared to VAM) to increased C supply. The CO₂ supplied at twice-ambient levels was shown to result higher numbers of mycorrhizal short root tips and a rapid rate of their colonization in white oak (*Quercus alba*) (O'Neill *et al.*, 1987). In another experiment, root colonization by *Pisolithus tinctorius* was also higher under elevated CO₂ on one population of loblolly pine (*Pinus faeda* L.), but not on another (Lewis *et al.*, 1992). Biomass of these seedlings in a low P treatment was greater at elevated CO₂ only in the population of seedlings that experienced enhanced colonization.

2.4.2 Soil C storage

Quite a few studies suggest that the terrestrial biosphere is removing large amounts of carbon dioxide from the atmosphere (Ciais *et al.*, 1995; Keeling *et al.*, 1996; Rayner *et al.*, 1999; Battle *et al.*, 2000; Schlesinger, 1984 and 1990), but the location of the stored carbon is a mystery. One possible location is in soil. Soil carbon and radiocarbon measurements collected worldwide suggest that soil carbon has the potential to significantly alter atmospheric carbon dioxide levels and to be the location of the "missing sink" [Harrison, 1996]. The potential changes of elevation of atmospheric CO₂ on C and N cycle are schematically represented in Fig. 3.

Several studies have looked at changes in soil carbon associated with carbon dioxide enrichment. Hungate and co-workers (1996 and 1997) have found that elevated carbon dioxide levels increased soil carbon input. Van

Fig. 3. Conceptual diagram highlighting the potential consequences of changing atmospheric CO₂ (Zak *et al.*, 1993)



Kessel and co-workers (2000) have observed that total soil carbon was not increased by carbon dioxide enrichment. Schlesinger and Lichter (2001) have reported that the elevated soil carbon inventory at the Duke FACE site was 20 per cent higher than the ambient inventory after three years of treatment. However, pre-treatment depth intervals (0–7.5, 7.5–15, 15–35 cm) differed from post-treatment depth intervals (0–15, 15–30 cm). Hagedorn and co-workers (2003) have found that the overall effect of CO₂ enrichment on soil carbon was small. Loya and associates (2003) have observed that CO₂ enrichment raised soil carbon levels by six per cent. Van de Geijn and Van Veen (1993) pointed out that it is not clear whether SOM pools will grow or decline under elevated CO₂. There have been a number of experiments examining changes in litter quality under elevated CO₂, and the effects of these changes on the ability of microbes to mineralize SOM (Cotrufo *et al.*, 1994; Coteaux *et al.*, 1991; Kemp *et al.*, 1994; Torbert *et al.*, 1998 and 2000; Van Veen *et al.*, 1996). This seems to be one major pathway through which elevated CO₂ concentrations will affect carbon storage in ecosystems. Beyond litter quality, however, there are probably other equally important ways by which changes in atmospheric CO₂ concentrations may drive altered carbon storage in soils. Elevated CO₂ may influence dynamics of SOM processing by causing altered rhizodeposition (O'Neill, 1994; Van de Geijn and Van Veen, 1993; Van Veen *et al.*, 1991; Luxmore *et al.*, 1986), and by changing soil water content *via* altered water use by plants (Hungate *et al.*, 1996), or both.

Altered decomposition will, in turn, affect nutrient availability to plants either positively (Zak *et al.*, 1993) or negatively (Diaz *et al.*, 1993), ultimately feeding back to influence net primary productivity. As Hungate and associates (1996) and Harrison and associates (1995) illustrated, because SOM pools are so large in comparison to annual inputs from vegetation, it is difficult to detect changes in pool sizes in the short time period of most elevated CO₂ experiments. However, the changes in the active pools of carbon are detectable and measurable even during the short-term experiments.

2.4.2.1 Labile carbon

Zak and co-workers (1993) reported that when exposed to elevated CO_2 there is an increase in labile carbon in rhizosphere soil of crops. However, no significant change was observed in the bulk soil with respect to the labile carbon content. Potassium permanganate - oxidizable C (labile C) is highly correlated with total C regardless of soil type (Padre *et al.*, 2001 Padre and Ladha, 2004).

Experiments conducted in four farmers' fields in the Philippines utilizing a rice (*Oryza sativa* L.) sweet pepper (*Capsicum annuum* L.) system aimed to determine the effects of different transition crops like indigo (*Indigofera tinctoria* L.), indigo plus mungbean (*Vigna radiata* L.) and corn (*Zea mays* L.) grown during the dry-to-wet transition on total and labile C pools showed a decrease in labile C with cropping which ranged from 6 per cent to 21 per cent and increase with residue incorporation ranging from 18 per cent to 37 per cent at different sites. But total C remained unchanged. The labile C balance indicated a loss of up to $1,438 \text{ kg ha}^{-1}$ due to farming practices and a gain of up to $3,077 \text{ kg ha}^{-1}$ with residue addition. Thus it is clear that labile C is sensitive to soil management practices, and thus provides a better measurement of C dynamics in the short to medium term than total C alone (Shreshtha *et al.*, 2002).

Gough and Seiler (2004) reported that forest soils store an immense quantity of labile carbon (C) and may be a large potential sink for atmospheric C.

2.4.2.2 Carbohydrate carbon

When plants are grown under elevated atmospheric CO_2 a common observation is that with the increased production of photosynthates there is a corresponding increase in the carbohydrates in the plant tissues. King and co-workers (2001) reported that elevated CO_2 and low soil nitrogen resulted in higher litter concentrations of non-structural carbohydrates and condensed tannins, higher C: N ratios and lower N concentrations in different plant materials. Soil N availability was found to have a greater effect on litter quality

than did atmospheric CO₂, although the treatments were additive as highest concentrations of non-structural carbohydrates and condensed tannins occurred under elevated CO₂-low soil N (King *et al.*, 2001). Fernandez and co-workers reported a decrease in soluble sugar and starch in cassava plants under elevated atmospheric CO₂ and the decrease in starch was found to coincide with the increase in root mass. Any change in plant materials will be reflected in the root exudations that, in turn might be reflected in the carbohydrate carbon status of soil.

However, there is no report available as such regarding the effect of elevation of CO₂ in atmosphere on carbohydrate carbon in soil.

2.4.2.3 Dissolved organic carbon

Tsherko and associates (2001) reported a significant increase in dissolved organic carbon in response to the elevation of atmospheric CO₂. Hagedorn and co-workers (2002) studied the effects of elevated CO₂ and increased N deposition on concentrations and properties of DOC collected with suction cups at 5 -10 cm depth and found that it was negligible. Export of DOC by drainage was reduced under elevated CO₂ in the calcareous sand (-22%), but concentrations were unaffected and the reduction was due to a secondary effect of reduced drainage. The differences in DOC between the two soils under study were large, indicating that soil properties had a greater influence on DOC than the CO₂ and N induced changes in above- and below-ground biomass. This was probably caused by the low input of 'new' (less than 4-yr-old) C into DOC and it indicated that potential sources of new C such as throughfall, litter leaching, and rhizodeposits made minor direct contributions to the DOC of the soil solution during the four experimental years (Hagedorn *et al.*, 2002). The increase of dissolved organic carbon (DOC) at higher CO₂ and temperature levels were found to favour significantly denitrification enzyme activity (Tsherko *et al.*, 2001). A 45-day incubation experiment was conducted under controlled laboratory conditions to study the interactive effects of elevated CO₂ and temperature on the dynamics of microbial biomass C and organic C in flooded paddy soil microcosms amended or unamended with rice straw. The microcosms with the two

treatments were transferred separately to four growth chambers to incubate them under 16 h/8 h light and dark conditions. Two of the growth chambers set at 25 and 35 degrees C provided a continuous flow of elevated CO₂ (equivalent to 800 micro l litre⁻¹). Similarly the other two growth chambers were run under near ambient CO₂ (400 micro l litre⁻¹) conditions at each of the two temperatures. The amounts of soluble carbon, microbial biomass C, chlorophyll-type compounds, and organic C in the surface (0-1 cm) and subsurface (below 1 cm) soil layers were measured at 15, 30, and 45 days after incubation. The amount of soluble carbon in the straw-amended soil gradually decreased throughout the incubation period, while no significant differences were detected among the four different conditions. The interactive effects of both elevated CO₂ and temperature were found to be positive in terms of the size of the microbial biomass in surface soil, although no significant differences were detected in the subsurface. However, the amount of total soil organic C was larger in the soils incubated at a lower temperature. The amounts of chlorophyll-type compounds doubled in the surface soil when the soils were incubated under elevated CO₂ conditions, indicating that the higher incubation concentration of CO₂ promoted the growth of algae in surface soil (Inubushi *et al.*, 1999).

2.5 LITTER QUALITY AND DECOMPOSITION

Litter decomposition plays a great role in ecosystem processes and carbon cycling and is therefore an important determinant of soil fertility and plant productivity. Thus, factors which regulate litter decomposition are important to ecosystem functioning (Swift *et al.*, 1979; Gorissen and Cotrufo, 2000). Decomposition rate is mainly affected by climate (temperature and precipitation) and by the chemical composition of leaf litter (Melillo *et al.*, 1982; Taylor *et al.*, 1989; Kemp *et al.*, 1994). It is still commonly assumed that rising atmospheric CO₂ will reduce leaf litter quality by increasing C:N and lignin:N ratios (Lamborg *et al.*, 1983; Strain and Bazzaz 1983; O'Neill and Norby 1996), and thus the decomposition rates in terrestrial ecosystems. It was further assumed that these reductions would lead to decreased rates of nutrient cycling and dampen the potential CO₂ stimulation of C sequestration

rates when exposed *in situ* in native plant communities. Despite this limited information, it is widely presumed that rising atmospheric CO₂ will lead to reductions in leaf litter quality and rates of decomposition in native plant communities, leading to reductions in nutrient availability (Melillo, 1983; Agren *et al.*, 1991 and McGuire *et al.*, 1995).

Cotrufo and Ineson (2000) reported that elevated CO₂ significantly affected the chemical composition of beech twigs, which had 38 per cent lower N and 12 per cent lower lignin concentrations than twigs grown under ambient CO₂. The sharp decrease in N concentration resulted in significant increase in the C/N and lignin/N ratios of the beech (*Fagus sylvatica*) wood grown at elevated CO₂. However, the elevated CO₂ treatment did not reduce the decomposition rates of twigs, neither were the dynamics of N and lignin in the decomposing beech wood (Cotrufo and Ineson, 2000).

As for non-lignified litter tissues, wood decomposition rates are the resultant of the interaction of three main factors: resource quality, microclimate and organisms (Rayner and Boddy, 1986). However, these factors may exert different relative effects on lignified tissues when compared to non-lignified materials and consequently, the impacts of elevated CO₂ found for leaf litter cannot be simply assumed for woody tissue. Elevated CO₂ has been predicted to affect litter decomposition *via* changes in litter quality, and several studies on tree leaf litter have confirmed this hypothesis (Cotrufo *et al.*, 1994, 1998 and Couteaux, 1991).

Elevated atmospheric CO₂ has the potential to influence rates of C and N cycling in terrestrial ecosystems by altering plant litter chemistry and slowing rates of organic matter decomposition. We tested the hypothesis that the chemistry of leaf litter produced at elevated CO₂ would slow C and N transformations in soil. Randlett and associates (1996) conducted an experiment in which soils were amended with populus leaf litter produced under two levels of atmospheric CO₂ (ambient and twice-ambient) and soil N availability (low and high). Kinetic parameters for microbial respiration and net N mineralization were determined on soil with and without litter during a 32-week laboratory incubation. Product accumulation curves for CO₂-C and

inorganic N were fit to a first order rate equation [$y = A(1 - e^{-kt})$] using nonlinear regression analyses. Although CO_2 treatment affected soluble sugar concentration in leaf litter (ambient = 120 g kg^{-1} , elevated = 130 g kg^{-1}), it did not affect starch concentration or C/N ratio. Microbial respiration, microbial biomass, and leaf litter C/N ratio were affected by soil N availability but not by atmospheric CO_2 . Net N mineralization was a linear function of time and was not significantly different for leaves grown at ambient (50 mg N kg^{-1}) and elevated CO_2 (35 mg N kg^{-1}) condition.

Even though from these studies a general conclusion cannot be derived, some recurrent relationships between decomposition rate and litter properties may indicate the existence of a common pattern:

1. Decomposition rate is negatively correlated with lignin concentration, phenolic compounds, lignin/N ratio, leaf toughness and some nutrient-concentration ratios;
2. Decomposition rate is positively correlated with manganese concentration, the concentration of the complex Ca+K+Mg, and the ratio HLQ (hemicellulose+cellulose / hemicellulose+cellulose+lignin) (Cortez *et al.*, 1996);
3. The correlation of the decomposition rate with the concentrations of nitrogen (N), phosphorus (P), potassium (K) and magnesium (Mg) may change according to the phase of the decomposition process (Angelis *et al.*, 2000).

2.6 MODELLING THE RESPONSES TO ELEVATED CO_2

Models are useful tools for organizing our thinking and for identifying critical gaps in our understanding of processes. In exploring effects of CO_2 on below ground processes, we must integrate experiments and models, with timely exchanges of information between the two approaches. At present, there is a need for increased feedback between ecosystem-level CO_2 studies and ecosystem modelling efforts.

Paustrian *et al.* (1996) used the CENTURY model to evaluate the interactions between climate change, carbon dioxide fertilization and management in influencing soil carbon levels in three agro ecosystems: a

conventional winter wheat - summer fallow rotation, a wheat-corn-fallow rotation and continuous cropping with wheat. The model analyses showed that management practice was more important than any aspect of climate change or CO_2 concentration in controlling soil carbon levels. Yiqi Luo of Desert Research Institute, USA has proposed another model to study the effects of elevated CO_2 on carbon accumulation in terrestrial ecosystems (Canadell *et al.*, 1996). A global version of CQUESTN was used to investigate past and future carbon sequestration in terrestrial ecosystems as influenced by increases in atmospheric CO_2 concentration, temperature and N deposition (Gifford *et al.*, 1996). Using reasonable estimates of global nitrogen and carbon pools, turn over times and fluxes, as well as credible mechanisms of ecosystem response, it is assumed that increases in CO_2 , temperature and N-deposition could account for a net terrestrial sink for carbon of $3\text{-}4 \text{ Gt yr}^{-1}$.

Parton from Colorado State University, USA showed the value of model intercomparison studies for advancing our understanding of the processes controlling carbon accumulation in ecosystems. Analysing the studies of the Vegetation/Ecosystem Modelling and Analysis Project (VEMAP Members, 1995), he came to the conclusion that elevated CO_2 and climate change showed diverging trends of results indicating the gaps of adequate research and knowledge about the controls on key ecosystem processes, especially under those novel conditions.

CERES model, a modification from PAPRAN model is very widely used to simulate C and N dynamics in soil. At the beginning of simulation, CERES assigns fixed percentages of plant residue dry matter to each of three pools, carbohydrate, cellulose and lignin. These three pools decompose simultaneously, each one having a decay rate constant under non-limiting conditions. Assigning a fixed percentage to each pool follows the philosophy of minimum data set, but it may greatly diminish the ability of the model to predict nitrogen mineralization (Quemada and Cabrera, 1995). In the original CERES model, decay rate constants under nonlimiting conditions were taken from the PAPRAN model (Seligman and Van Keulen, 1981; Godwin and Jones, 1991). The original values were 0.8, 0.05 and 0.0095 day^{-1} for

carbohydrate, cellulose and lignin respectively. The actual values used in the model in particular conditions were obtained by adjusting the decay rates based on environmental conditions. Vijil and co-workers in 1991 modified the respective values of decay rates to 0.05, 0.0045 and 0.00095 day⁻¹ for carbohydrate, cellulose and lignin. Later, Bowen and associates modified the decay rate parameters to 0.2, 0.05 and 0.0095 day⁻¹ for carbohydrate, cellulose and lignin, respectively.

In the present study CERES model is tested and modified to predict carbon and nitrogen mineralization under elevated atmospheric CO₂ conditions.

2.7 STUDIES IN INDIA

Sengupta conducted an experiment at IARI in 1988 to study the effect of increasing CO₂ concentration on photosynthesis and photorespiration in wheat leaf. He used different concentration of CO₂ i.e., 100, 340, 600, 1000, 3400, 10,000 ppm and observed that in wheat leaves photosynthetic rate was doubled when CO₂ concentration was increased from 100 ppm to ambient 340 ppm and from 340 ppm to 600 ppm. Sharma and Sengupta (1990) also reported positive effect of CO₂ in *Vigna radiata*.

In 1996, Uprety and Mahalaxmi studied the effect of elevated CO₂ and nitrogen on physiological characters of *Brassica juncea* at IARI, New Delhi. They reported that elevated CO₂ significantly increased the carbon contents of leaf, stem and root.

Abrol and his associates in 1996 studied comparative response of C₃ (mungbean) and C₄ (maize) cultivars to elevated CO₂ in OTCs. They reported that rise in CO₂ concentration in the atmosphere brought about significant increase in the dry weight of leaves in mungbean varieties. However stem dry weight did not show any significant increase due to elevated CO₂. In case of maize neither leaf nor stem dry weight was affected by CO₂.

Dwivedi and co-workers (1997) studied the interactive effect of rising atmospheric carbon dioxide and drought on the nutrient constituents of *Brassica juncea* seed. Elevated CO₂ significantly reduced (10.3%) the protein

content of seeds. Moisture stress also decreased the protein content. However, the reduction was not significant at elevated CO₂ level. The CO₂ enrichment increased oil content (10.4%) whereas moisture stress caused a marked reduction (7.2%) in it. The stress-induced reduction was not significant under elevated CO₂ condition. The author suggested that the reduction in protein content in seeds might be due to accumulation of carbohydrates causing dilution effect. Reduced transpiration led to reduction in N uptake and less protein content in *Brassica juncea*.

Kumari and co-workers in 1998 conducted an experiment to study the effect of elevated CO₂ on growth and yield of rice variety Pusa 834. They recorded yield components of rice as panicle number (effective tillers), filled grains per panicle and grain weight. In their investigation all the components increased at high CO₂ but the general contribution of grain weight was less than other two because the husk physically limited the size of grains. The grain number per panicle increased because high CO₂ overcame factors that cause flower degeneration during ear development. Further, sufficient photo-assimilate supply might have increased the maturity per cent of seeds. They commented that future studies are needed to quantitatively assess the extent up to which the predicted effects of doubled-CO₂ limits on rice yield can be mitigated by using different cropping seasons and cultivars.

3. MATERIALS AND METHODS

The materials and methods related to the study on “**Carbon dynamics and nitrogen mineralization in soil under elevated atmospheric CO₂ conditions**” have been described under the following heads:

- 3.1 Experimental site
- 3.2 Pot culture experiment (Open Top Chamber)
- 3.3 Field experiment (Free Air Carbon dioxide Enrichment technology)
- 3.4 Decomposition study (Phytotron chambers)
- 3.5 Analytical procedures
- 3.6 Initial characteristics of the experimental soils
- 3.7 CERES-N model
- 3.8 Statistical analysis

3.1 EXPERIMENTAL SITE

The experiments have been conducted in the research farm area behind the Division of Plant Physiology, Indian Agricultural Research Institute (IARI) and in closed phytotron chambers at National Phytotron Facility situated at IARI, New Delhi.

New Delhi is situated at latitude of 28°40' N, longitude of 77°12' E and elevation of about 228 m above mean sea level. It has semi-arid subtropical climate with hot dry summer and cold winter.

3.2 POT CULTURE EXPERIMENT

The pot culture experiment was conducted in Open Top Chambers (OTCs) situated within the compound of Division of Plant Physiology.

3.2.1 Soil

Soils which have been exposed to elevated and ambient CO₂ concentrations during the *rabi* season of 2003-04 to conduct another pot culture experiment with wheat were used to conduct the pot culture experiments of current investigation. Soils had been previously collected from

IARI Farm and belong to inceptisol order (Typic Haplustept). The initial characteristics of the soils are given in Table 1.

3.2.2 Crops

Rice and wheat crops were taken in a sequence in the *kharif* and *rabi* seasons of the year 2004-2005. Rice (*Oryza sativa*) cultivar Pusa Sugandh and wheat (*Triticum aestivum*) HD 2687 were chosen as test crops to study the carbon dynamics in soil as influenced by increase in atmospheric CO₂ concentrations.

3.2.3 Pots

Earthen pots of seven kg capacity of soil were used for growing rice crop. The pots were lined from inside by folded polythene sheets to facilitate the maintenance of water level for rice crop.

Polypropylene pots of four kg capacity of soil were used for growing the wheat crop. Each pot was provided with a hole at the bottom for draining excess water. In normal condition the holes were kept closed with rubber cork.

3.2.4 Carbon dioxide (CO₂) gas

Pure CO₂ gas (99.7% v/v CO₂ and less than 10 ppm CO) was used to increase the level of carbon dioxide inside OTC.

3.2.5 Open Top Chamber (OTC)

To characterize the responses of crop plants, CO₂ enrichment technique was followed for exposure of crops to elevated CO₂ under near natural conditions. Open top chambers comprise five sub systems as shown schematically in Figure 4a.

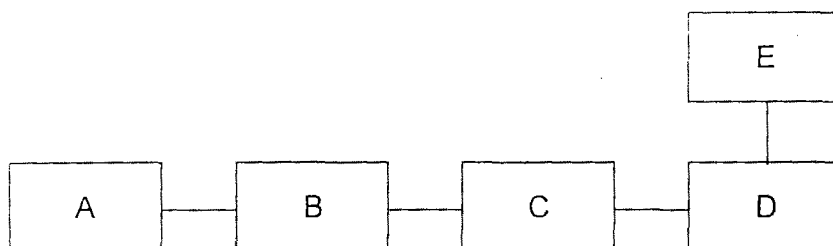
The open top chambers used in the study were made of an aluminium frame installed on the ground (Fig. 4b). The height of each OTC was 1.8 m and diameter was 1.5 m. Chambers were covered with transparent polyvinyl chloride sheet equipped with a frustum at the top to deflect air and prevent dilution so as to maintain the desired CO₂ concentrations within the chambers. Top of the chamber was kept open for free air exchange thus providing near natural conditions. The PVC sheet allowed more than 85 per cent of incident solar radiation to pass through. The chamber has an automatic closing door, which was used for taking observations and for doing inter-cultural practices.

Table 1. Initial characteristics of the experimental soils used for pot culture study in OTC

Parameter	Ambient soil	Elevated soil
Organic carbon (%)	0.36	0.38
Available P (kg ha ⁻¹)	38.0	31.4
Available K (kg ha ⁻¹)	213	218
MBC (mg kg ⁻¹)	202.4	203.8
DOC (mg kg ⁻¹)	43.27	43.21
CHC (mg kg ⁻¹)	1275	1276
LBC (mg kg ⁻¹)	1185	1191
Total soil carbon (g kg ⁻¹)	7.10	7.11
Textural class	Sandy loam	Sandy loam

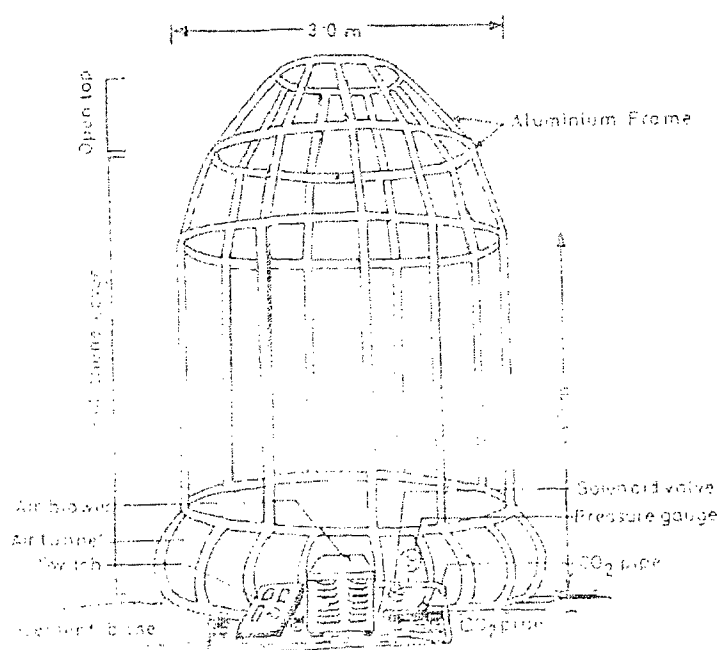
Fig. 4. Basic schematic depiction and a representative diagram of Open top chamber (OTC) technology.

a) Basic scheme of measurement and control system for CO₂ enhancement in open top chamber technology.



- (A) Supply of pure and high concentration of CO₂
- (B) System of valves, regulators and flow meters
- (C) Chambers or area to be CO₂ controlled
- (D) Appropriate gas analyzer with feed back control
- (E) Computed data acquisition and programming

b) A representative diagram of Open Top Chamber.



At the base of the chamber there was a hollow circular PVC ring through which CO₂-air mixture was blown into the chamber. Commercial CO₂ was added upstream of the frame to ensure adequate mixing and to create the desired concentration. Blowers were used to ensure forced entry of CO₂-air mixture inside the chamber. The pure CO₂ gas coming from the cylinder was diluted with ambient air through proper mixing facilitated by the blower. Then the mixture of CO₂ and air was injected into the OTC. The desired level of CO₂ concentration inside the chamber was attained through the control mechanisms of regulators and flow meters. A representative diagram of an OTC is shown in Figure 4b.

Two open chambers, one maintained at ambient CO₂ and the other at elevated CO₂ concentrations were used for the present investigation (Plate 1). The level of CO₂ within the OTC was monitored using portable Infrared Gas Analyzer (IRGA) (Model No. LI-COR 6200). The air from different levels and positions inside the chamber was drawn through nylon tubing and directed into the IRGA. Desired level of CO₂ inside OTC was obtained by adjusting the flow meter and gas regulator. Every day morning their positions were checked and adjusted. In control chamber, only ambient air was supplied through blower to maintain all the environmental factors similar to elevated chamber CO₂ level.

3.2.6 Treatments

For the rice-wheat cropping system in followed OTCs, the treatments were as given below:

a) CO₂ levels

Two levels of carbon dioxide as mentioned below were maintained during the entire course of the experiments inside the OTCs.

1. Ambient (approximately 372 $\mu\text{mol mol}^{-1}$) and
2. Elevated (600 ± 50 $\mu\text{mol mol}^{-1}$) levels of carbon dioxide

b) Physiological stages

Four physiological stages of both rice and wheat as mentioned below were chosen for destructive sampling of soil (rhizosphere) and plant lots.

Plate 1. Open Top Chambers (ambient and elevated CO_2) used in the study with rice crop at maximum tillering stage (*Kharif* season, 2004).



Rice

- | | | |
|------------------------|---|-----------------------------------|
| 1. Tillering stage | : | 25 Days after transplanting (DAT) |
| 2. Flowering stage | : | 55 DAT |
| 3. Grain filling stage | : | 85 DAT |
| 4. Maturity stage | : | 110 DAT |

Wheat

- | | | |
|--------------------------------------|---|----------------------------|
| 1. Crown root initiation stage (CRI) | : | 25 days after sowing (DAS) |
| 2. Anthesis stage | : | 57 DAS |
| 3. Grain filling stage | : | 95 DAS |
| 4. Maturity | : | 118 DAS |

c) Replications : Three

3.2.7 Design of experiment

The experiment was laid out in a two factor completely randomized design.

3.2.8 Raising of the crops

The pot culture experiment with rice and wheat as test crops in rotation was conducted in OTCs available with the Division of Plant Physiology, IARI, New Delhi during the *kharif* and *rabi* seasons of 2004-2005, respectively. The cultivation practices followed for rice and wheat are given under separate headings.

3.2.8.1 Rice crop

a) Processing of the soil

Soils those had been used in the previous *rabi* season (2003-04) for growing wheat crop in pots under elevated and ambient atmospheric CO₂ conditions were collected, dried in shade and mixed thoroughly in separate (elevated and ambient) lots to attain uniformity. Certain lots of soil samples were kept aside for analyzing the initial parameters.

b) Residue incorporation and pot filling

Seven kg soil was taken on a polythene sheet. Wheat residues grown at elevated and ambient CO₂ conditions were collected, dried, chopped well and mixed with the soil @ 62.5 g pot⁻¹ which corresponds to 20 t ha⁻¹). Residue collected from elevated and ambient CO₂ conditions were added to

the pots with soil that were used for growing crops under elevated and ambient CO₂ concentrations respectively. Thorough mixing was done and then filled into respective pots.

The pots were kept as such for fifteen days to allow the decomposition of residues before further addition of nutrients and transplanting.

c) Addition of nutrients

The soils in pots was again taken out on a polythene sheet and thoroughly mixed with fertilizer solution containing N, P and K through solution of urea, single super phosphate (SSP) and muriate of potash (MOP), respectively. Applied fertilizer doses were 250 per cent of recommended dose (190:75:25 kg N, P₂O₅ and K₂O per hectare) for rice crop based on soil test values. After thorough mixing, the fertilized soils were refilled into respective pots.

d) Transplanting and inter cultural operations

About seven to eight seedlings of rice were transplanted into the pots. Ten to fifteen days after establishment, seedlings were thinned out to maintain 5 plants per pot. About 2-3 cm standing water level was maintained throughout the growing period, excepting the last two weeks of maturity. The plants were grown up to different physiological stages as per the treatments followed by destructive sampling. After each stage sampling the pots along with the remaining soil were kept inside OTCs.

3.2.8.2 Wheat crop

a) Processing of the soil

Pots with soil, which had been used for growing rice crop in *kharif* season, were used for sowing wheat crop in the *rabi* season. Soil in each pot was mixed well and dried in shade.

b) Residue incorporation and pot filling

Four kg soil was taken on a polythene sheet and mixed with the dried, chopped rice residues at the rate of 35.7 g pot⁻¹, which corresponds to 20 t ha⁻¹. Residues collected from elevated and ambient CO₂ conditions were mixed with the soils in pots kept in elevated and ambient OTCs, respectively. Thorough mixing was done and soils were filled into the respective pots.

c) Addition of nutrients

The soils in pots were again taken out on a polythene sheet and thoroughly mixed with fertilizer solutions containing N, P and K through solution of urea, single superphosphate (SSP) and muriate of potash (MOP), respectively. Applied fertilizer doses were 200 per cent of recommended dose (120:60:40 kg N, P_2O_5 and K_2O per hectare) based on soil test values. The fertilized soils were mixed well and refilled into respective pots.

d) Sowing and intercultural operations

About 2-3 seeds of wheat (Cv. HD 2687) were sown in each pot. A handful of soil was removed before sowing and was spread on the sown seeds to ensure uniform cover. Ten to fifteen days after germination, seedlings were thinned out to maintain three plants per pot. The plants were grown up to different physiological (CRI, anthesis and maturity) stages as per the treatments to facilitate destructive sampling.

3.2.9. Collection and processing of plant and soil samples

3.2.9.1 Plant samples

The harvest of rice and wheat crops were done according to the physiological stages as mentioned in treatments.

a) Above ground plant parts

Depending on the physiological stage at which the plants were harvested, the above ground portions with stem plus leaves were collected. For those pots harvested at maturity stage, the grains were collected separately and seeds were separated and stored. The collected biomass as well as the grains were first dried in shade followed by drying in hot air oven at $70^{\circ}C$ till constant weight was achieved. Dry weight of both biomass and grains were recorded. Further, the plant biomasses were ground through a Willey mill.

b) Root

The soil inside the pot was taken out on a plastic sheet and roots were separated carefully. The whole root mass was washed over a fine sieve under gently flowing tap water. After thorough washing, the roots were dipped in de-ionized water and subsequently excess water was soaked in blotting paper. Fresh root weight and root volume were determined as such. The roots were

dried in air followed by drying in oven at 70 °C and grinding to facilitate the determination of C and N contained in them.

3.2.9.2 Soil samples

Soil samples were collected at different physiological stages of rice and wheat crops through destructive sampling of the pots. During the separation of the soil from the roots, those adhered loosely to the roots were discarded after gentle shaking and the rest of the soils strongly adhered to the roots were treated as rhizosphere soil. One half of the soil was stored afresh for determination of microbial biomass carbon (MBC), ammoniacal and nitrate nitrogen, and the other half was dried in shade and processed through 2 mm sieve for the determination of other soil parameters. The fresh rhizosphere soil was preserved at 4 °C and pre-incubated to normal temperature overnight just before the actual determination.

3.2.10 Parameters measured in both rice and wheat crops

Soil

- a) Microbial Biomass Carbon
- b) Dissolved organic carbon
- c) Carbohydrate carbon
- d) Labile carbon
- e) Total soil carbon
- f) Ammoniacal nitrogen
- g) Nitrate nitrogen

Plant samples (Stem, leaf and roots)

- a) Dry weights of all parts
- b) Root fresh weight and root volume
- c) Total carbon
- d) Total nitrogen

3.3 FIELD EXPERIMENT (FREE AIR CARBON DIOXIDE ENRICHMENT TECHNOLOGY)

3.3.1 Site

This experiment was conducted in the farm area behind the Division of Plant Physiology. The soil belongs to Typic Haplustept group and the initial physico-chemical properties of the soil are given in Tables 2 and 3.

Table 2. Initial characteristics of the experimental soils used for raising crops in field (FACE)

Parameters	Ambient soil	Elevated soil
Organic carbon (%)	0.44	0.46
Available P (kg ha ⁻¹)	49.3	88.8
Available K (kg ha ⁻¹)	319	455

Table 3. initial carbon pools (depth wise) of the experimental soils used for raising crops in field (FACE)

Parameters	Depths of soil (cm)			
	0-5	5-10	10-15	15-20
Ambient field				
MBC (mg kg ⁻¹)	211.4	213.0	196.6	170.5
DOC (mg kg ⁻¹)	57.70	55.27	54.63	54.16
CHC (mg kg ⁻¹)	1450	1385	998.1	796.1
LBC (mg kg ⁻¹)	1079	959.8	642.0	535.0
TSC (g kg ⁻¹)	10.74	9.50	8.25	7.18
FACE soil				
MBC (mg kg ⁻¹)	209.8	220.4	197.2	168.5
DOC (mg kg ⁻¹)	60.14	54.46	55.19	54.25
CHC (mg kg ⁻¹)	1461	1394	998.8	796.1
LBC (mg kg ⁻¹)	1086	985	642.6	533.8
TSC (g kg ⁻¹)	10.82	9.61	8.24	7.18

3.3.2 Crops

Rice and wheat crops were taken in a sequence in the *kharif* and *rabi* seasons of the year 2004-2005. Rice (*Oryza sativa*) cultivar Pusa Sugandh-2 and wheat (*Triticum aestivum*) HD 2687 were chosen as test crops to study the carbon dynamics in soil as influenced by elevation of atmospheric CO₂ concentrations.

3.3.3 Free Air Carbon dioxide Enrichment Technology (FACE)

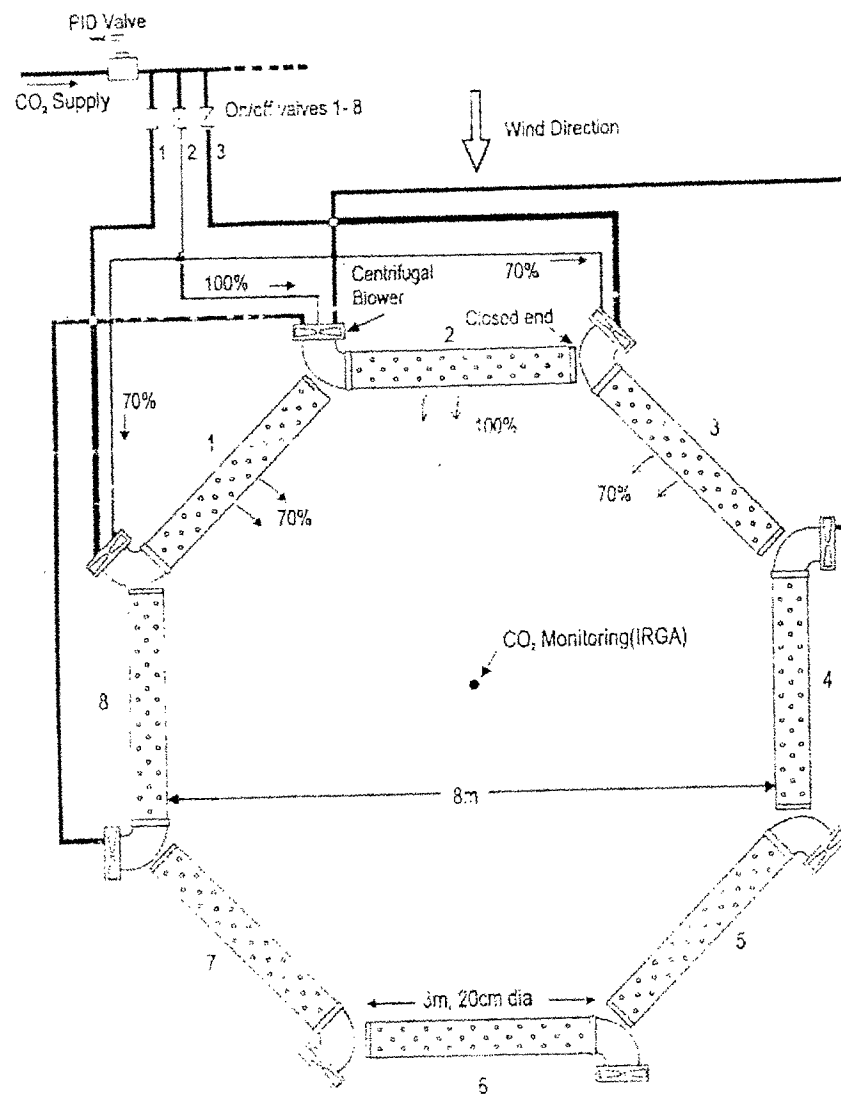
FACE technology was based on the principle of injecting additional CO₂ gas in open field suitably so as to attain pre-determined elevated level of gas concentration with uniform distribution in the field under varying meteorological conditions of wind, temperature and humidity. The main components of a FACE facility were:

1. CO₂ gas storage and distribution system.
2. The FACE ring, generally known as plenum, through which CO₂ enriched air was injected into the open field.
3. Different sensors and actuators used for monitoring the environment and controlling the operations.
4. An electronic system for controlling these various operations.

3.3.3.1 System design

The Mid-FACE ring is octagonal in shape having a diameter of 8 m as shown in the schematic diagram (Fig. 5). The eight arms of the FACE ring are made of rigid PVC pipes of 200 mm diameter and wall thickness of 4.5 mm. Each arm of the octagon is fitted with a centrifugal air blower at one end for blowing air into the pipe and is closed at the other end. Four rows of holes (4 mm dia) are drilled on each arm for the outlet of CO₂-enriched air. The CO₂ is injected at the input of each air blower for pre-mixing with air within the pipe before its injection in the fields. The air blower pressure and holes on the pipe are arranged in such a way that the air outlet from the holes along the whole length of pipe remains at uniform pressure. All the eight arms of the octagon have independent supply of CO₂ controlled by 8 on/off valves. A common computer controlled proportional integral differential (PID) valve controls the quantity of CO₂ to be released into the arms.

Fig. 5 Lay out schematic of Mid FACE facility.



The CO₂ is released at a time into the field from 3 adjacent arms of the FACE ring. For each arm there are three nozzles for CO₂ injection. Depending on the downward wind direction, the central arm gets CO₂ from the nozzle having 1.5 mm dia and adjacent arms, get supply from nozzles having 1.0 mm dia. As shown in Fig. 5, when the downward wind direction is towards the arm 2 side, the on/off valve No. 2 is switched on and CO₂ is released from the arms 1, 2 and 3. The CO₂ is injected into the arm 2 through the nozzle of 1.5 mm dia and into the arms 1 and 3 through the nozzle of 1.0 mm dia to take care of the effect of tilt of adjacent arms with wind direction. Thus, at any given time, for any wind direction, CO₂ is always released only through 3 arms of the FACE ring/plenum.

The CO₂ concentration is measured at the centre of the field with the help of an Infra-Red Gas Analyser (IRGA WMA-2). Sampling of gas is done continuously through a thin polythene tubing (4.3 mm dia) with the inlet height adjusted at about 5-25 cm above the crop canopy. The output from IRGA is a DC voltage in the range of 0-5 V corresponding to 0-2000 ppm of CO₂.

The concentration of CO₂ in open fields not only depends on the quantity of CO₂-enriched air released from the plenum, but also on the gas dispersion characteristics controlled by the meteorological factors such as wind speed, wind direction, humidity and temperature within the plenum. The sensors for wind speed (anemometer), wind direction (wind vane) and temperature are located near the centre of the FACE ring at plant canopy height. Their output signals are continuously measured in real time by the system controller.

The fumigation of CO₂ gas into the field from the plenum is made at the crop canopy height. The height of plenum can be adjusted from time to time to match with the height of the crop canopy by resting the plenum on height-adjustable stands. Plenum can be raised up to 5 feet from the ground level in steps of 2 inches. Two banks of 25 cylinders in parallel are used for CO₂ storage and dissemination under constant pressure. Normally, one bank of cylinders supplies CO₂ to the ring. The second bank is switched on when CO₂ gets exhausted in the 1st bank. A buffer tank has been installed after the

cylinder bank, which takes care of the pressure variations in the supply line due to decreasing level of CO₂ in the cylinders during Mid-FACE operation.

3.3.3.2 Control system

The control process involves monitoring of CO₂ concentration and meteorological parameters inside the FACE ring along with the issue of control signals to a number of devices for their proper operation. A PC-based system controller is designed to control all such operations of the FACE facility. The data from the meteorological sensors (wind speed and wind direction) along with the CO₂ concentration are measured every one second by the control system. Then 1, 5 and 15 min averages, along with their deviations from the instantaneous (every 1 second) values, are computed. Based on these inputs, the control system, through a specially developed PID algorithm, controls the flow rate of CO₂ gas in the plenum with the help of a PID controller value. The FACE facility used in the experiment with rice crop is given in Plate 2.

3.3.4 Treatment combinations

3.3.4.1 CO₂ level

Two levels of carbon dioxide as mentioned below were maintained during the entire course of experiment.

1. Ambient (approximately 372 $\mu\text{mol mol}^{-1}$) and
2. Elevated ($600 \pm 50 \mu\text{mol mol}^{-1}$) level of carbon dioxide

3.3.4.2 Physiological stages

Four physiological stages of both rice and wheat as mentioned below were chosen for sampling of soil and plant lots.

Rice

- | | | |
|------------------------|---|-----------------------------------|
| 1. Tillering stage | : | 25 Days after transplanting (DAT) |
| 2. Flowering stage | : | 55 DAT |
| 3. Grain filling stage | : | 85 DAT |
| 4. Maturity stage | : | 110 DAT |

Wheat

- | | | |
|--------------------------------------|---|----------------------------|
| 1. Crown root initiation stage (CRI) | : | 25 days after sowing (DAS) |
| 2. Anthesis stage | : | 57 DAS |

Plate 2. Free Air Carbon dioxide Enrichment (FACE) facility with rice crop in *kharif* season, 2004.



- | | | |
|------------------------|---|---------|
| 3. Grain filling stage | : | 95 DAS |
| 4. Maturity | : | 118 DAS |

3.3.4.3 Depths of soil

Soil samples were collected from the crop rhizospheres at four depths:

1. 0-5 cm,
2. 5-10 cm,
3. 10-15 cm and
4. 15-20 cm

Spacing: 20 cm x 20 cm

3.3.5 Raising of the crops

3.3.5.1 Rice

In the FACE experiment seeds of rice were sown in the nursery and after 25 days, the seedling were hand-transplanted. In the main fields of FACE hand transplanting was used to ensure an even number of seedling per hill. The main field was prepared by hoeing. Farmyard manure (FYM) was applied @ 5 t ha⁻¹ at the time of field preparation. Hills and rows were 20 and 120 cm apart respectively. The N:P:K applied was @ 100:40:40 kg ha⁻¹ in the form of urea, single super phosphate and potash, respectively. The N was supplied in 3 split doses, with application of 50 per cent of the total N as basal; 25 per cent at mid-tillering stage and the remaining 25 per cent at panicle-initiation stage. Fields were flooded throughout the season with the exception of 10 days before harvest. Manual weeding was done to remove the weeds.

3.3.5.2 Wheat

After thorough ploughing and land preparation FYM and fertilizers were applied @ 5 t ha⁻¹ (FYM) and 100:40:40 kg ha⁻¹ N:P:K respectively. Seeds of wheat were sown by broadcasting and uniformity was maintained by thinning out the excess seedlings after one to two weeks. ^{Nitrogen} N was supplied in three splits just like that of rice; 50 per cent basal, 25 per cent at CRI and the other 25 per cent at anthesis.

3.3.6 Sampling and processing of the soil

3.3.6.1 Sampling

Soil samples were collected from different depths using tube auger at different physiological stages of growth of rice and wheat. Irrigation was done one day prior to every sampling to facilitate easy sampling of soil from the four depths.

3.3.6.2 Processing

Soil samples were collected from the four depths at the four physiological stages of rice and wheat as mentioned in treatments. One half of the soils were taken for determination of microbial biomass carbon (MBC), ammoniacal and nitrate nitrogen, while the other half was dried in shade and processed through 2 mm sieve for the determination of other parameters. The fresh rhizosphere soil was preserved at 4 °C and pre-incubated to normal temperature overnight just before the actual determination.

3.3.7 Parameters measured

Soil

- a) Total carbon
- b) Microbial Biomass Carbon
- c) Dissolved organic carbon
- d) Carbohydrate carbon
- h) Labile carbon

3.4 DECOMPOSITION STUDY

3.4.1 Soil

Soil used in the decomposition study was collected from IARI Farm (Typic Haplustept) during December 2004 and the initial characteristics are given in Table 4.

3.4.2 Residues

Rice and wheat residues produced in elevated and ambient CO₂ conditions were collected from the FACE experiment of the year of 2004 and the initial characteristics are given in Table 5.

3.4.3 Pots

Poly propylene pots of 500g capacity of soil were used for the decomposition study.

Table 4. Initial characteristics of the soil used for decomposition study in phytotron chambers

Parameters	Values
Total organic carbon (TOC) (%)	0.601
Ammoniacal nitrogen (kg ha ⁻¹)	40.3
Nitrate nitrogen (kg ha ⁻¹)	66.7
MBC (mg kg ⁻¹)	156.2

Table 5. Initial characteristics of the residues used for decomposition study in phytotron chambers

	Ambient CO ₂ -grown rice (RA)	Elevated CO ₂ -grown rice (RE)	Ambient CO ₂ -grown wheat (WA)	Elevated CO ₂ -grown wheat (WE)
Carbon (%)	41.28	42.26	44.00	44.21
Nitrogen (%)	0.62	0.59	0.51	0.49
C:N ratio	67.12	72.28	86.27	90.42
Weight taken	5.625	5.625	5.625	5.625

3.4.4 Nylon bags and plastic threads

The nylon cloths of 60 mesh and plastic threads were bought from the market.

3.4.5 Treatment combinations

3.4.5.1 CO₂ level

1. Ambient (approximately 372 $\mu\text{mol mol}^{-1}$) and
2. Elevated (600 ± 50 $\mu\text{mol mol}^{-1}$) levels of carbon dioxide

3.4.5.2 Time of sampling

Destructive sampling of pots with litterbags were done at different days of decomposition as shown below:

1. 15 days of decomposition
2. 30 days of decomposition
3. 45 days of decomposition
4. 60 days of decomposition
5. 75 days of decomposition
6. 90 days of decomposition
7. 105 days of decomposition
8. 120 days of decomposition
9. 135 days of decomposition
10. 150 days of decomposition

3.4.5.3 Residues

(i) Rice

1. Ambient CO₂-grown rice residues (RA):- Collected from plants grown under ambient atmospheric CO₂ condition in ambient field.
2. Elevated CO₂-grown rice residues (RE):- Collected from plants grown under elevated atmospheric CO₂ condition in FACE field.

(ii) Wheat

1. Ambient CO₂-grown wheat residues (WA):- Collected from plants grown under ambient atmospheric CO₂ condition in ambient field.
2. Elevated CO₂-grown wheat residues (WE):- Collected from plants grown under elevated atmospheric CO₂ condition in FACE field.

3.4.5.4 Replication : 6

3.4.5.5 Design

The experiment was laid out in two factor completely randomized design.

3.4.6 CO₂ enrichment technology- Phytotron chambers

Phytotron chambers maintained at ambient ($350 \mu\text{mol mol}^{-1}$) and elevated ($600 \pm 50 \mu\text{mol mol}^{-1}$) CO₂ concentrations were used for investigating the kinetics of residue decomposition in these conditions. These chambers were available with the National Phytotron Facility, Indian Agricultural Research Institute, New Delhi. Those were enclosed chambers wherein temperature, humidity, sunlight and CO₂ concentrations were controlled and regulated by means of programmed softwares. Two chambers were allotted for the experiment, one maintained at higher CO₂ concentrations and the other at ambient concentration. Temperature and relative humidity of both the chambers were programmed at 25°C and more than 80 per cent, respectively. Natural day light hours and dark hours were simulated as such with the help of incandescent lamps (Plate 6).

3.4.7 Processing of the soil and residues

The collected soil was passed through 2 mm sieve dried in shade and mixed well to attain uniformity.

The four residues (ambient and elevated rice-wheat) were dried in shade and were chopped well to small pieces of less than half a centimeter size.

3.4.8 Preparation of nylon bags and pot filling

The nylon cloth was cut into square pieces of 10 cm x 10 cm size. 5.625 g of well-chopped dried residue was placed on the cloth piece, made into bags by folding from all sides and tied with the help of plastic threads (Plate. 3). The litterbag was inserted into the centre of the pot, and soil (420 g) was filled (Plate 4). One litterbag was placed in each pot. Care was taken to avoid contact between the litterbag and the walls of the pot, thus covering the litterbags by soil from all sides.

T-7577



Plates 3 and 4. Litterbags and pots with litterbags inserted into soil used in decomposition study

Plate 3



Plate 4



Plate 5. Pots with litter bags arranged on racks inside the phytotron chambers



Plate 6. Phytotron chamber (maintained at elevated CO₂) used in the decomposition study



3.4.9 Experimental setup and maintenance

The pots containing litterbag inserted into the soil were kept inside the phytotron chamber in multistoried racks as shown in Plate 5. Pots with rice and wheat litterbags from elevated CO₂ field were kept in the chamber maintained at higher CO₂ concentration (Plate 6) and ambient ones in the chamber remained at ambient (normal) CO₂ concentrations.

Programme for temperature, humidity and sunshine hours were adjusted for both the chambers. Pure CO₂ gas was supplied into the respective chamber, with elevated CO₂ and concentration was maintained at 650 $\mu\text{mol mol}^{-1}$ throughout the period of the experiment.

Distilled water was added once in every two and three days and soil moisture was maintained near about field capacity level (25% w/w) by monitoring gravimetrically.

3.4.10 Collection and processing of soil and residue samples

Destructive sampling of the pots [12 from ambient chamber (6 rice + 6 wheat) and similarly 12 from elevated chamber] was done at every fifteen days interval for the five-month period.

3.4.10.1 Residue

The litterbag was taken out and washed with little distilled water to remove the adhered soil particles in to the pot. The bag was opened and the residues were washed in standing water and kept for air-drying followed by drying in the oven at 70°C till constant weight is achieved. Dry weights of the samples were noted down and were ground through a Willey mill to facilitate the analysis of the residue samples.

3.4.10.2 Soil

Soil in pot was mixed well and divided into two halves. One half of the soil was taken for determination of microbial biomass carbon (MBC) and ammoniacal and nitrate nitrogen, while the other half was dried in shade and processed for the determination of total organic carbon status. The fresh soil (for MBC and nitrogen analysis) was preserved at 4°C and pre-incubated to normal temperature overnight, just before the actual determination.

3.4.11 Parameters measured

Residue

- a) Amount remaining inside the litterbag
- b) Total carbon
- c) Total nitrogen

Soil

- a) Total organic carbon
- b) Microbial biomass carbon
- c) Ammoniacal nitrogen
- d) Nitrate nitrogen
- i) Field capacity, wilting point and soil moisture levels
- j) Soil temperature

3.5 ANALYTICAL PROCEDURES

3.5.1 Plant samples

3.5.1.1 Yield and growth related parameters

a) Root volume

Root volume was determined by the displacement method.

b) Dry root weight

Root dry weight after oven drying was recorded at 70 °C till constant weight is achieved.

c) Stem and leaf dry weights

Oven dry weight of leaf and stem were recorded.

d) Grain dry weight

Dry weight of the grains after oven drying was also noted down.

3.5.1.2 Total carbon content in plant samples

Total carbon in soil sample was determined by wet oxidation diffusion method given by Snyder and Trofymow (1984). Plant sample was taken in a diffusion tube and about 1 g $K_2Cr_2O_7$ and 25 ml of mixture (3:2) of concentrated $H_2SO_4:H_3PO_4$ (85%) were added. An amount of 4 ml of 2 N NaOH was taken in a vial and was quickly inserted into the diffusion tube and kept over the constriction to serve as the CO_2 trap. The diffusion tube was tightly capped. Then it was digested at 120°C for two hours in a digestion block (Gerhardt Kjeldatherm). A control was also run without soil

sample. The unconsumed NaOH in the vial was estimated by titration with standard 1N HCl using phenolphthalein indicator. During titration, saturated BaCl₂ solution was added to convert the trapped CO₂ as BaCO₃ thus preventing its reaction with acid.

3.5.1.3 Total nitrogen

Nitrogen in the dried plant sample was estimated following the prescribed procedure (Technican Monograph, 1971) using Nitrogen Autoanalyser. The method consisted of two main steps: (i) the plant material was digested to convert various forms of nitrogen to ammonia; and (ii) measurement of ammonia in digested plant sample was carried out after conversion into indophenol dye.

Digestion

The digestion of plant samples was done according to a modified version of Kjeldahl procedure. Generally 25-250 mg of finely ground material was used depending on the stage of the plant growth and plant parts. Accurately weighed dried plant samples were transferred to a digestion tube of 75 ml capacity. In each tube, 4 ml of digestion mixture was added along with a digestion tablet supplied by Kjeltabs Auto Thompson and Capper Ltd, manufacturing chemists, Liverpool, England.

The digestion mixture consisted of concentrated H₂SO₄ and H₃PO₄ of AR grade in the ratio of 20:1 by volume. Each digestion tablet contained 1.5 g of potassium sulphate and 0.0075 g of selenium as catalyst. Sets of 40 samples were digested on a Tecater digestion unit at a temperature of 250-300°C. Then 1.5 ml of 3 per cent v/v H₂O₂ was added to each tube. Subsequent to digestion, the volume was made up to 75 ml with distilled water. Each set of 40 samples included one of known standard concentration.

Estimation of nitrogen

The nitrogen content in the digested samples was estimated using Technician Autoanalyser. The NH₃, which was present in the digested sample, reacted with the alkaline hypochlorite to form chloramine. Further,

reaction of chloramine with phenol gave a blue indophenol dye. The intensity of the indophenol dye was directly proportional to ammonium concentration, which was automatically read at 630 nm in a colorimeter and recorded as a peak on the chart. The nitrogen content of the samples was then read out using a calibration curve obtained by running a series of standards of ammonium chloride solutions in the autoanalyser (ranging from 0.5 mg to 5 mg N per ml) containing similar amount of acid and salt as in the sample digested. From the values thus obtained, per cent N was calculated as given below:

$$\% \text{ N} = \frac{\text{Chart reading} \times 100}{\text{Sample weight (mg)}}$$

3.5.2 Soil samples

3.5.2.1 Microbial biomass carbon (MBC)

MBC in soil was analysed by the procedure given by Horwath and Paul (1994). Two sets of 10g fresh soil was taken in beakers, the first one was fumigated with chloroform for 24 hrs, while the other set was kept unfumigated. Both the fumigated and unfumigated soil samples were extracted using 0.5M K₂SO₄. Small amount of the extract was digested with potassium persulphate (K₂S₂O₈) at 120°C for two hours in a digestion block (Gerhardt Kjeldatherm). The carbon dioxide evolved during digestion was trapped in 0.1N NaOH taken in a vial kept over the constriction inside the digestion tube. A control was also run taking 0.5M K₂SO₄ in place of the extract. The unconsumed NaOH was determined by titration with standard 0.01N H₂SO₄ using phenolphthalein indicator. The MBC was calculated by using the formula given below and reported on oven dry soil basis.

$$\text{MBC (mg/kg)} = (C_F - C_{UF}) / K_{EC}$$

Where,

- C_F - Carbon in fumigated soil
- C_{UF} - Carbon in unfumigated soil
- K_{EC} - Efficiency of extraction (0.25)

3.5.2.2 Dehydrogenase activity

Dehydrogenase activity in soil was determined by Triphenyl Tetrazolium Chloride (TTC) method as outlined by Klein *et al.* (1971). One gram air dry soil sample was taken in air-tight screw capped test tube, 0.2 ml of 3 per cent TTC solution and 0.5 ml of 1 per cent glucose solution was added in each test tube to saturate the soil. Tubes were gently tapped to drive out all trapped oxygen to ensure water seal and then incubated at 28 ± 0.5 °C for 24 hours. After incubation 10 ml of methanol was added in each tube, shaken vigorously and allowed to stand for 6 h. The clear pink coloured supernatant indicating the presence of Triphenyl Formazan (TPF) in alcohol phase was measured spectrophotometrically at a wavelength of 485 nm (blue filter). Standard TPF solution were used as reference and result was expressed in terms of mg TPF formed per hour per air dry gram soil.

3.5.2.3 Labile carbon

Labile carbon in soil sample was determined by 0.333 M KMnO_4 oxidation method as described by Blair and co-workers (1995). A 25 ml portion of 0.333 M KMnO_4 solution was added to five-gram air-dry soil sample, taken in a centrifuge tube and shaken for 1 h. The samples were centrifuged for 5 min at 2000 rpm and the supernatant was diluted 250 times with distilled water. The absorbance of diluted samples and standard KMnO_4 solution were read on a spectrophotometer at 565 nm. The change in the concentration of KMnO_4 was used to determine the amount of carbon oxidized, assuming that 1 mM KMnO_4 has been consumed ($\text{Mn VII} \sim \text{Mn IV}$) during the oxidation of 0.75 mM or 9 mg of carbon.

3.5.2.4 Dissolved organic carbon

Dissolved organic carbon (DOC) in soil sample was determined by water extraction method (Burford and Bremner, 1975) followed by carbon estimation through per-sulphate digestion method (Horwath and Paul, 1994). A 1:2 w/v soil:water extract was prepared by shaking fresh soil sample with distilled water on a reciprocating shaker for 15 minutes. Then it was centrifuged at 9500 rpm to get a clear extract. The supernatant was vacuum filtered through fritted disk filter of medium pore size. The DOC was

determined in water extract through per-sulphate digestion as described in MBC determination procedure.

3.5.2.5 Carbohydrate carbon

Carbohydrate carbon in soil sample was determined by Anthrone blue colour method (Brink *et al.*, 1960). Five-gram air-dry soil was passed through 1 mm sieve and then hydrolysed with 50 ml of 3N H₂SO₄ for 24 h on a steam bath maintained at 85°C. Hot hydrolysate was passed through a fritted disc filter of medium pore size and residue left above the filter was washed with 50 ml hot water. The filtrate was allowed to cool at room temperature and volume was made up to 100 ml with distilled water. Five ml of diluted soil hydrolysate was mixed with 10 ml of Anthrone reagent and absorbance of the green colour was read at 625 nm taking water-anthrone as blank. Standard curve was prepared using standard glucose solution and then carbohydrate carbon in soil was calculated.

3.5.2.6 Total carbon content in soil

Total carbon in soil sample was determined by wet oxidation diffusion method (Snyder and Trofymow, 1984) taking 1 g soil sample and proceeding further as given in the procedure for total carbon determination in plant samples.

3.5.2.7 Total organic carbon content in soil

Total organic carbon in soil sample was determined by wet oxidation diffusion method (Snyder and Trofymow, 1984) taking 1 g soil sample and adding 3 ml of 2N HCl to remove the inorganic carbon. Then proceeded further as given in the procedure for total carbon determination in plant samples.

3.5.2.8 Ammoniacal nitrogen and nitrate nitrogen

About three grams of fresh soil was extracted with 30 ml of 2M KCl for 1h. Extracts were then analysed for NH₄-N by steam distillation with MgO in a microkjeldahl system and then proceeded for nitrate-N after reduction with Devarda's alloy followed by distillation (Bremner and Keeney, 1966). The ammonia evolved was trapped in 2 per cent boric acid containing mixed indicator (0.099 g bromocresol green and 0.066 g methyl red dissolved in 100 ml of 95% ethanol) and then determined by titrating with approx. 0.002 N

H₂SO₄. The concentration of H₂SO₄ used for titration and the weight of soil taken for preparing extracts were changed whenever needed.

3.4.5.2.9 Field capacity and wilting point

Field capacity and wilting point were measured using pressure plate apparatus.

3.4.5.2.10 Soil temperature

Soil temperature in the potted soil was measured with the help of a thermometer.

3.6 INITIAL CHARACTERISTICS OF THE EXPERIMENTAL SOILS

3.6.1 Organic carbon

Walkley and Black titration was followed using sulphuric acid, phosphoric acid, potassium dichromate and ferrous ammonium sulphate with diphenyl amine indicator (Walkley and Black, 1934).

3.6.2 Mineralisable nitrogen

The alkaline potassium permanganate oxidisable soil nitrogen was estimated as an index of available nitrogen (Subbiah and Asija, 1956).

3.6.3 Available P

0.5 M Sodium bicarbonate (pH 8.5) extract of the soil was taken (Olsen *et al.*, 1954) and P content was read calorimetrically by the ascorbic acid method.

3.6.4 Available K

Neutral normal ammonium acetate extractable K was determined through flame photometer (Hanway and Heidel, 1952).

3.6.5 Mechanical analysis

Particle size distribution of the soil passing through 2 mm sieve was determined by using Bouyoucos hydrometer as outlined by Bouyoucos (1962).

The initial characteristics of the soils used for potculture experiment, field experiment and decomposition study are presented in Tables 1, 2, 3, 4 and 5.

3.7 CERES-N MODEL

It is a C and N process model originated from PAPRAN model. CERES-N divides the fresh organic pool (residue) into three sub-pools of

carbohydrate, cellulose and lignin each with its own C/N and degradation rate (Fig. 6).

3.7.1 Approach of the model

CERES simulates soil N transformations, including mineralization, immobilization, nitrification, and denitrification (Godwin and Jones, 1991). Briefly the mineralization and immobilization subroutine simulates the decay of two types of organic matter: fresh organic matter (FOM) and humus (HUM). The model requires the dry weight of the fresh residue applied and its C:N ratio and from these values fresh organic N (FON) is calculated. At the beginning of simulation, FOM is divided into three pools: 20 per cent of FOM goes to carbohydrate, 70 per cent to the cellulose fraction and 10 per cent to lignin. The three pools decompose simultaneously, each one having a maximum rate constant of decomposition that was obtained by repeated number of runs and re-runs for fitting the model to the experimental results. Those rate constants were put to the model to explain the behaviour under particular set of conditions. These rate constants were modified daily by three multiplicative factors based on C/N ratio of the residue, soil moisture and soil temperature in the corresponding soil layer.

Thus the minearlisation rate of the three fresh residue pools simulated in the CERES model are:

$$G1(j) = TF \times MF \times CNRF \times RDECR(j)$$

where,

$G1(j)$ is the proportion of the pool j ($j=1$ for carbohydrate, $j=2$ for cellulose and $j=3$ for lignin) that decays in one day

$RDECR(j)$ is the decay rate constant of the pool j

TF is the temperature factor

MF is the moisture factor and

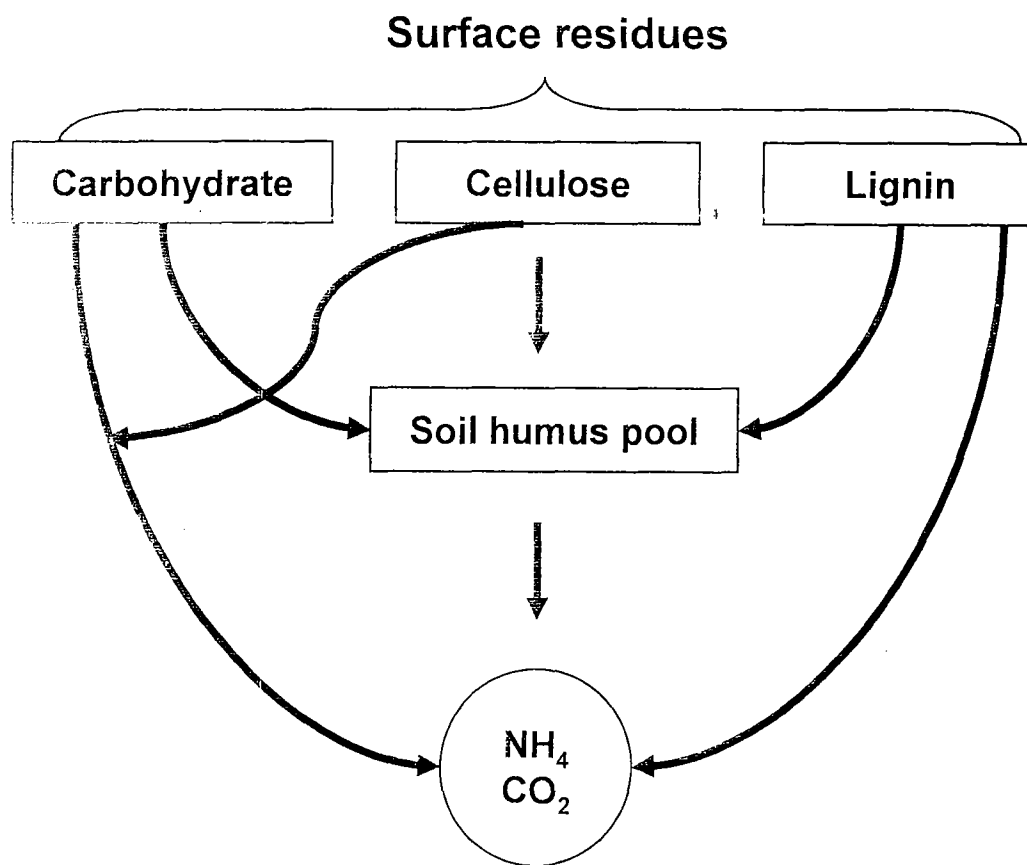
$CNRF$ is the C/N ratio factor.

Soil moisture and temperature constraints on N mineralization from organic matter (either HUM or FOM) are described by two nondimensional factors, MF and TF , respectively.

Temperature factor $TF = (ST-5)/30.0$ where, ST is the soil temperature

Moisture factor $MF = (\theta-WP)/(FC-WP)$ where, θ is the soil moisture content,

Fig. 6. The conceptual structure of organic C/N pools used in the CERES model



WP is the wilting point and FC is the field capacity moisture levels. Actually, the lower and upper limits of drainage given in the original model were taken as wilting point and field capacity, *respectively*.

The C/N ratio factor (CNRF) is given by:

$$\text{CNRF} = \exp \{-0.693[(\text{CNR}-25.0)/25.0]\}$$

Where, CNR is a C/N ratio obtained by dividing the C in FOM by the sum of the total inorganic N in soil and N in FOM. If CNRF > 1, the value of CNRF is set to one.

3.7.2 Approach for N mineralization

The model assumes that 20 per cent of the N mineralized is incorporated into HUM, the rest enters the soil inorganic pool and can be immobilized, leached, denitrified, or taken up by plants. The N immobilized is the minimum of two values: soil inorganic N and the demand of N by the decomposition of fresh organic matter (FOM). The demand of N by microorganisms (0.02 units of N per unit of dry matter) is calculated by multiplying the fraction of C in FOM (0.4) by the biosynthesis efficiency of microorganisms (0.4), and then dividing by the C:N ratio of the microbial biomass (8). FOM is assumed to have a carbon content of 40 per cent, which was suiting to the residues taken for study. The rate constant for HUM was taken as 0.00005 in all conditions.

In the present study, we used data from decomposition study using litterbag technique in phytotron to evaluate the original CERES and to determine the best fitting rate constants of decomposition for the carbohydrate, cellulose and lignin pools in the model so as to fit to the observed results. The rate constants were obtained by repeated number of runs and re-runs.

Another modification was done regarding the preference of ammonium for the process of immobilization. The original CERES assumes that microorganism firstly deplete the ammonium pool during immobilization and then only look for the nitrate pool. This was not followed as such in the present results. So the model was modified by including the proportional intake of nitrate nitrogen also by microbes during the process of immobilization.

3.8 STATISTICAL ANALYSIS

The data generated were subjected to various statistical analyses as outlined by Gomez and Gomez (1984) using MSTATC.

The results obtained from pot culture studies in OTCs were analyzed using two factor-CRD taking level of CO₂ and stages of growth as the two factors. Duncan's multiple range tests (DMRT) was performed (at 5 % level of significance) to arrange the data in descending order based on critical difference.

The data obtained from field studies in FACE were analyzed using three factor-CRD taking level of CO₂, stages of growth and depth of soil as the three factors of variation. DMRT was performed (at 5 % level of significance) to arrange the data in descending order based on critical difference.

The results obtained from decomposition study in phytotron were analyzed using two factor-CRD with levels of CO₂ (residues grown under ambient and elevated CO₂) and days of decomposition as the two factors. Here also DMRT was performed (at 5 % level of significance) to arrange the data in descending order based on critical difference.

The goodness of fit of the CERES model under different conditions was analyzed using chi-square test.

4. RESULTS AND DISCUSSION

The results from the current investigation have been presented and discussed in this chapter under the following sections:

- 4.1 Pot culture study -Rice and wheat
- 4.2 Field experiment-Rice and wheat
- 4.3 Decomposition study-Rice and wheat residues
- 4.4 Simulation of decomposition using CERES model
- 4.5 General discussion

Results from all the four sets of experiments are discussed in this chapter one by one.

4.1 POT CULTURE STUDY

Rice and wheat crops were taken in *kharif* and *rabi* seasons of 2004-05 and plant and soil samples were collected and analysed for different parameters. The results of pot culture study conducted in Open Top Chambers (OTCs) are given in detail under the following headings and sub headings:

4.1.1 Rice crop

4.1.1.1 Plant parameters

A. Plant biomass and partitioning

- a) Stem dry weight
- b) Leaf dry weight
- c) Root dry weight
- d) Grain dry weight
- e) Total biomass yield and partitioning in rice
- f) Fresh root weight
- g) Root volume

B) Carbon and nitrogen uptake and partitioning in rice

- a) Carbon content and uptake by stem

- b) Carbon content and uptake by leaf
- c) Carbon content and uptake by root
- d) Carbon content and uptake by grain
- e) Total carbon uptake and partitioning
- f) N content and C:N ratio of stem
- g) N content and C:N ratio of leaves
- h) N content and C:N ratio of roots
- i) N content and C:N ratio of grain

4.1.1.2 Soil parameters

A. Carbon pools

- a) Microbial biomass carbon
- b) Dissolved organic carbon
- c) Carbohydrate carbon
- d) Labile carbon
- e) Total soil carbon

B. Inorganic nitrogen pools

- a) Ammoniacal nitrogen
- b) Nitrate nitrogen

4.1.2 Wheat crop

4.1.2.1 Plant parameters

A. Plant biomass and partitioning

- a) Stem dry weight
- b) Leaf dry weight
- c) Root dry weight
- d) Grain dry weight
- e) Total biomass yield and partitioning in wheat
- f) Fresh root weight
- g) Root volume

B. Carbon and nitrogen uptake and partitioning in wheat

- a) Carbon content and uptake by stem
- b) Carbon content and uptake by leaf
- c) Carbon content and uptake by root
- d) Carbon content and uptake by grain

- e) Total carbon uptake and partitioning
- f) N content and C:N ratio of stem
- g) N content and C:N ratio of leaves
- h) N content and C:N ratio of roots
- i) N content and C:N ratio of grain γ

4.1.2.2 Soil parameters

A. Carbon pools

- a) Microbial biomass carbon
- b) Dissolved organic carbon
- c) Carbohydrate carbon
- d) Labile carbon
- e) Total soil carbon

B. Inorganic nitrogen pools

- a) Ammoniacal nitrogen
- b) Nitrate nitrogen

4.1.3 Gains in active carbon pools in rice and wheat rhizospheres

4.1.4. Relative build up of active C pools in rice and wheat rhizospheres

4.1.5. Interrelations between plant and soil parameters

4.1.1 Rice crop

4.1.1.1 Plant parameters

A. Plant biomass and partitioning

a) Stem dry weight

Stem dry weight of rice as affected by the levels of CO₂ and stages of crop growth are presented in Figure 7. Exposure to higher atmospheric CO₂ concentration increased the stem dry weight by 18.80 per cent over 29.56 g pot⁻¹ recorded under ambient CO₂ conditions (Fig. 7a). With age of the crop stem dry weight increased, reached maximum at grain filling stage and decreased further towards maturity (Fig. 7b).

The interaction of the levels of CO₂ with stages of growth was significant and the values are presented in Table 6. Highest stem dry weight was obtained at grain filling stage under elevated CO₂, which was followed by the weight at maturity. Stem dry matter accumulation at maturity under elevated CO₂ was on par with that at grain filling under ambient CO₂. At all

Fig. 7. Stem dry matter (g pot^{-1}) of rice grown in OTC as influenced by:

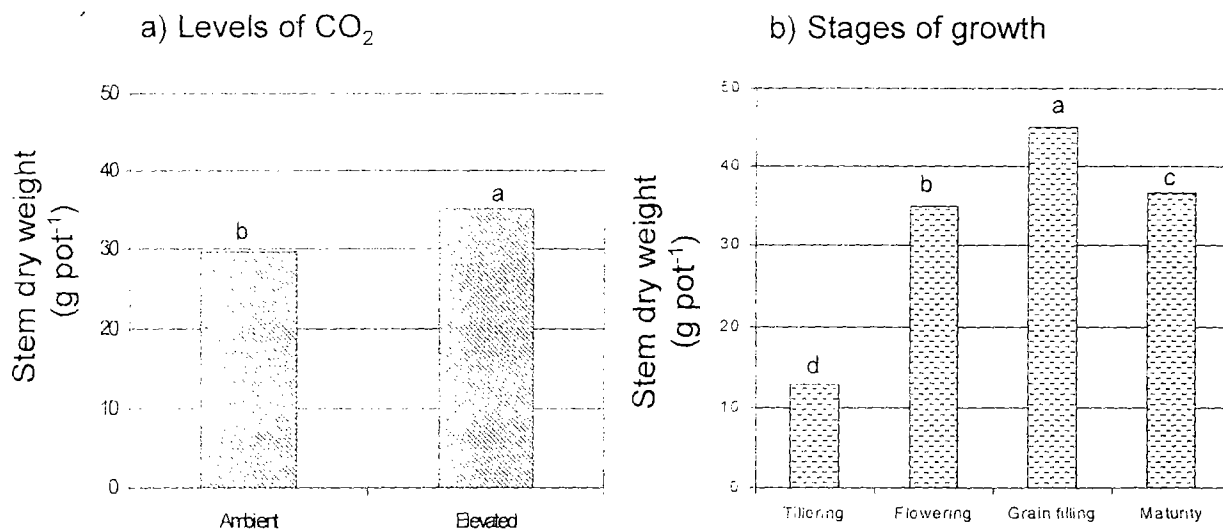


Table 6. Stem dry matter (g pot^{-1}) of rice grown in OTC as influenced by the interaction of levels of CO₂ and stages of crop growth

Growth stages	Levels of CO ₂	
	Ambient	Elevated
Tillering	12.22 ^e	13.47 ^e
Flowering	31.63 ^d	38.24 ^c
Grain filling	40.86 ^b	49.31 ^a
Maturity	33.52 ^d	39.69 ^{bc}

The differences between values with any common alphabet in figures or table are not statistically significant and *vice versa*

stages of crop growth (except tillering), the stem dry matter was higher under elevated atmospheric CO₂ when compared to ambient conditions. Tillering stage was probably too early to show any positive effect of higher CO₂.

b) Leaf dry weight

Average leaf dry weight of rice crop as influenced individually by the levels of CO₂ and stages of crop growth are depicted in Figure 8. Average leaf dry weight increased from 13.10 g pot⁻¹ under ambient CO₂ to 18.86 g pot⁻¹ under elevated CO₂ conditions, thus amounting to an increase of 43.97 per cent (Fig. 8a). Further, leaf dry weight continuously increased from tillering to flowering stage, remained same till grain filling and further decreased towards maturity (Fig. 8b).

The interaction effect of levels of CO₂ and stages of crop growth on leaf dry weight of rice was also significant and the values are presented in Table 7. There was no significant difference between the two CO₂ levels at tillering stage. Other three stages exhibited positive effect of elevation of atmospheric CO₂. Under ambient CO₂, leaf dry weight increased till flowering and then remained as such till maturity without any significant change. While, under higher CO₂, a decrease was observed between grain filling and maturity stages.

c) Root dry weight

Values pertaining to root dry matter as affected by levels of CO₂ and stages of crop growth are presented in Figure 9. Treatments belonging to ambient CO₂ produced an average root dry weight of 11.93 g pot⁻¹ while those belonging to elevated CO₂ produced 16.10 g pot⁻¹ (Fig. 9a), thus signifying an increase by 34.95 per cent. With the crop growth, root dry weight increased from tillering to flowering stage and subsequently decreased towards maturity (Fig. 9b). Changes were significant between each of the stages. Such decrease in root weight after flowering stage is ascribed to the probable decay of root mass and its turn over in rhizosphere.

Interaction effect was significant and the values are presented in Table 8. Highest root dry weight was produced at flowering stage under elevated CO₂ condition. The values of root dry weight under elevated CO₂ at all stages

Fig. 8. Leaf dry matter (g pot⁻¹) of rice grown in OTC as influenced by:

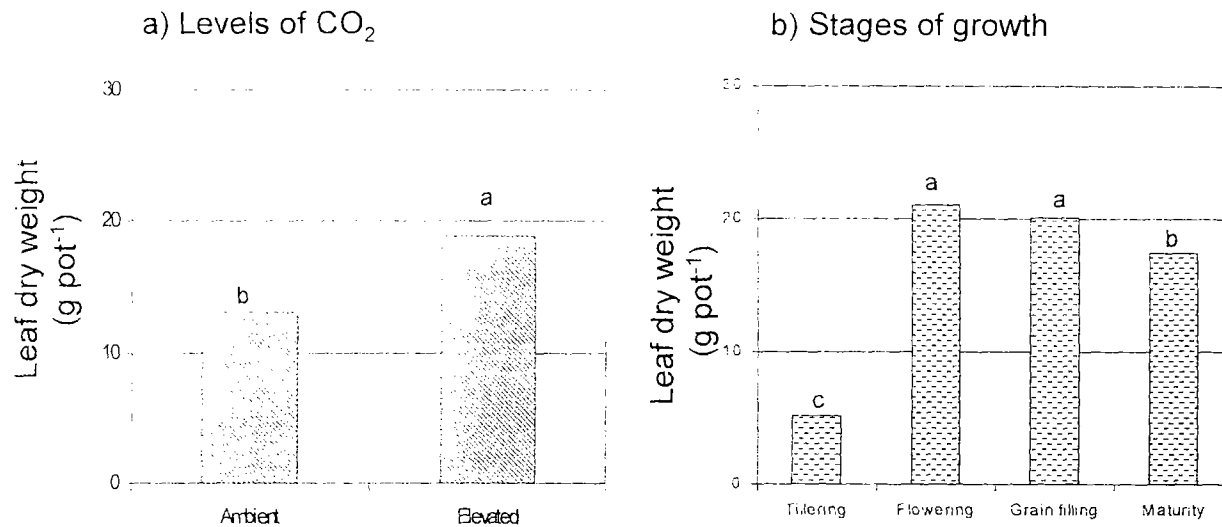


Table 7. Leaf dry matter (g pot⁻¹) of rice grown in OTC as influenced by the interaction of levels of CO₂ and stages of crop growth

Growth stages	Levels of CO ₂	
	Ambient	Elevated
Tillering	4.83 ^d	6.04 ^d
Flowering	16.46 ^c	25.53 ^a
Grain filling	15.86 ^c	24.25 ^a
Maturity	15.24 ^c	19.61 ^b

The differences between values with any common alphabet in figures or table are not statistically significant and *vice versa*

Fig. 9. Root dry matter (g pot^{-1}) of rice grown in OTC as influenced by:

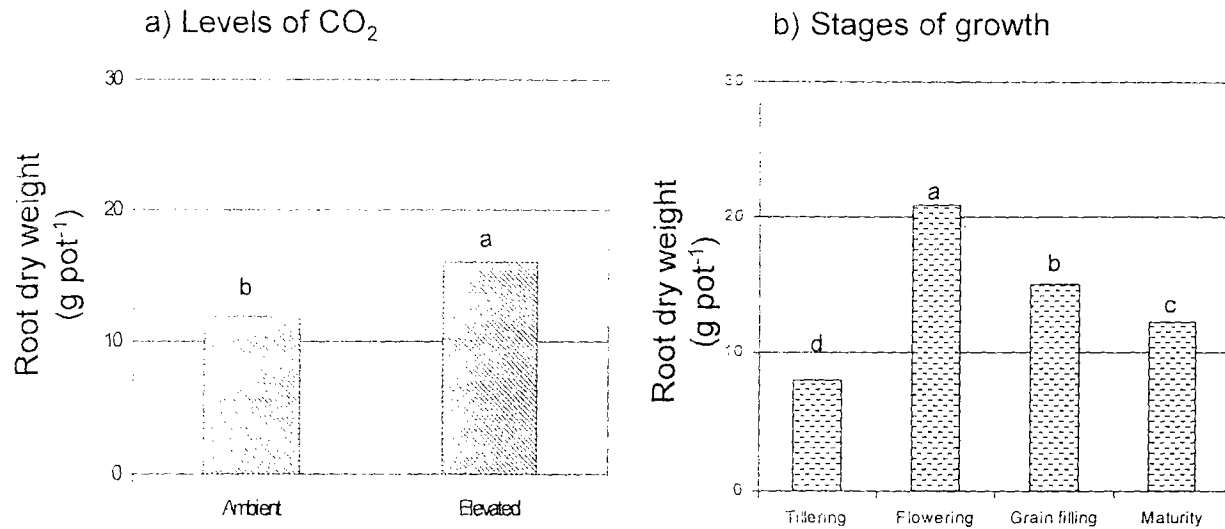


Table 8. Root dry matter (g pot^{-1}) of rice grown in OTC as influenced by the interaction of levels of CO_2 and stages of crop growth

Growth stages	Levels of CO_2	
	Ambient	Elevated
Tillering	7.197 ^e	8.690 ^e
Flowering	17.09 ^b	24.60 ^a
Grain filling	12.87 ^c	17.17 ^b
Maturity	10.56 ^d	13.94 ^c

The differences between values with any common alphabet in figures or table are not statistically significant and *vice versa*

of growth were higher than the corresponding values under ambient CO₂ conditions.

d) Grain weight

The weight of rice grains as affected by elevation of atmospheric CO₂ is given in Figure 10. Elevation of CO₂ in atmosphere had increased grain yield by 48.11 per cent from a value of 14.84 g pot⁻¹ under ambient CO₂ to 21.98 g pot⁻¹ under elevated CO₂ condition.

e) Total plant biomass and its partitioning

The effects of levels of CO₂ and stages of crop growth on total dry matter yield of rice are presented in Figure 11. Elevation of atmospheric CO₂ concentration increased the total biomass of rice from 57.18 g pot⁻¹ under ambient CO₂ to 75.63 g pot⁻¹, amounting to an increase of 32.26 per cent (Fig. 11a).

With relation to growth stages, total biomass yield increased continuously and significantly from tillering to maturity (Fig. 11b). Eventhough root weight and stem dry weight decreased towards maturity of the crop (Fig. 7b and 9b), the total biomass showed increasing trend even up to maturity. This can be attributed to the contribution from grain weight. The rate of increase in biomass yield was highest between tillering and flowering stage as this phase represents the most active period of vegetative growth.

Interaction between stages of crop growth and levels of CO₂ was also significant and the values are recorded in Table 9. At all stages of growth, total biomass yield was always higher under elevated CO₂ concentration. Highest biomass yield was produced at maturity stage elevated CO₂. Total biomass yield of the crop at flowering under elevated CO₂ was on par with the value at grain filling stage under elevated CO₂. In ambient condition, grain filling and maturity stages of rice did not exhibit any significant difference with respect to total biomass yield.

Increase in atmospheric CO₂ concentration significantly affected the biomass distribution pattern in rice. The distribution patterns at different stages of rice growth under ambient and elevated atmospheric CO₂ conditions are depicted in Figure 12. Irrespective of the levels of CO₂, per cent biomass allocation to roots decreased with age of the crop. Such decrease during the

Fig. 10. Grain weight (g pot⁻¹) of rice grown in OTC as influenced by the elevation of atmospheric CO₂ concentration

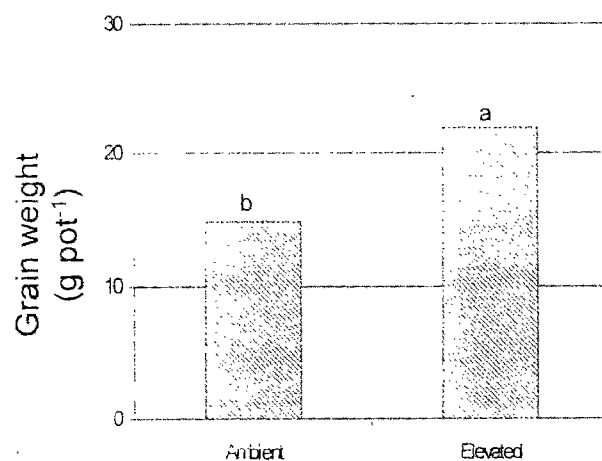
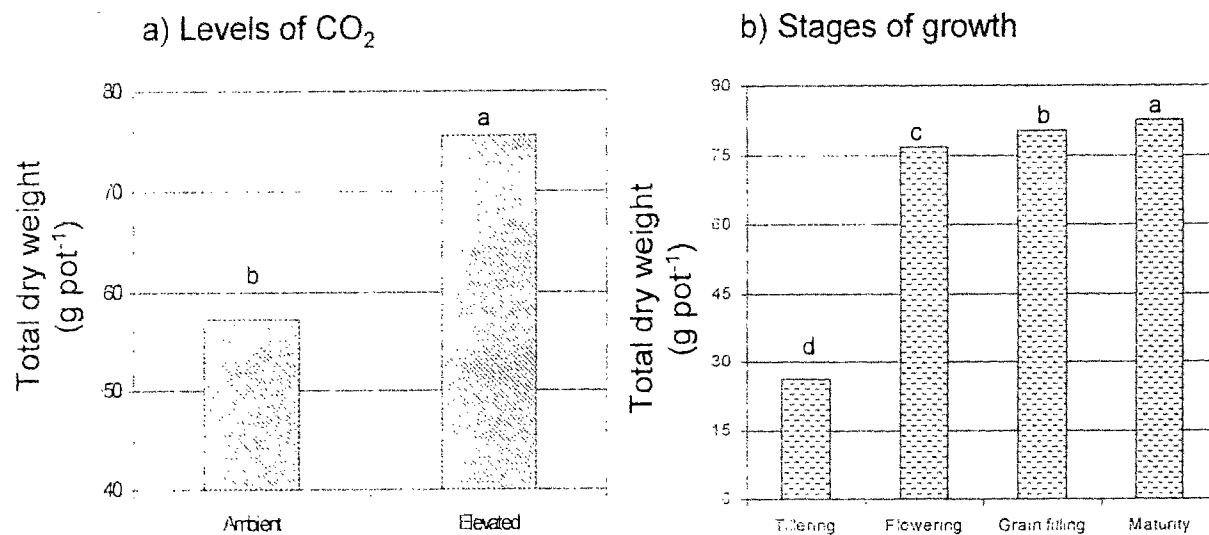


Fig. 11. Total dry matter yield (g pot⁻¹) of rice grown in OTC as influenced by:



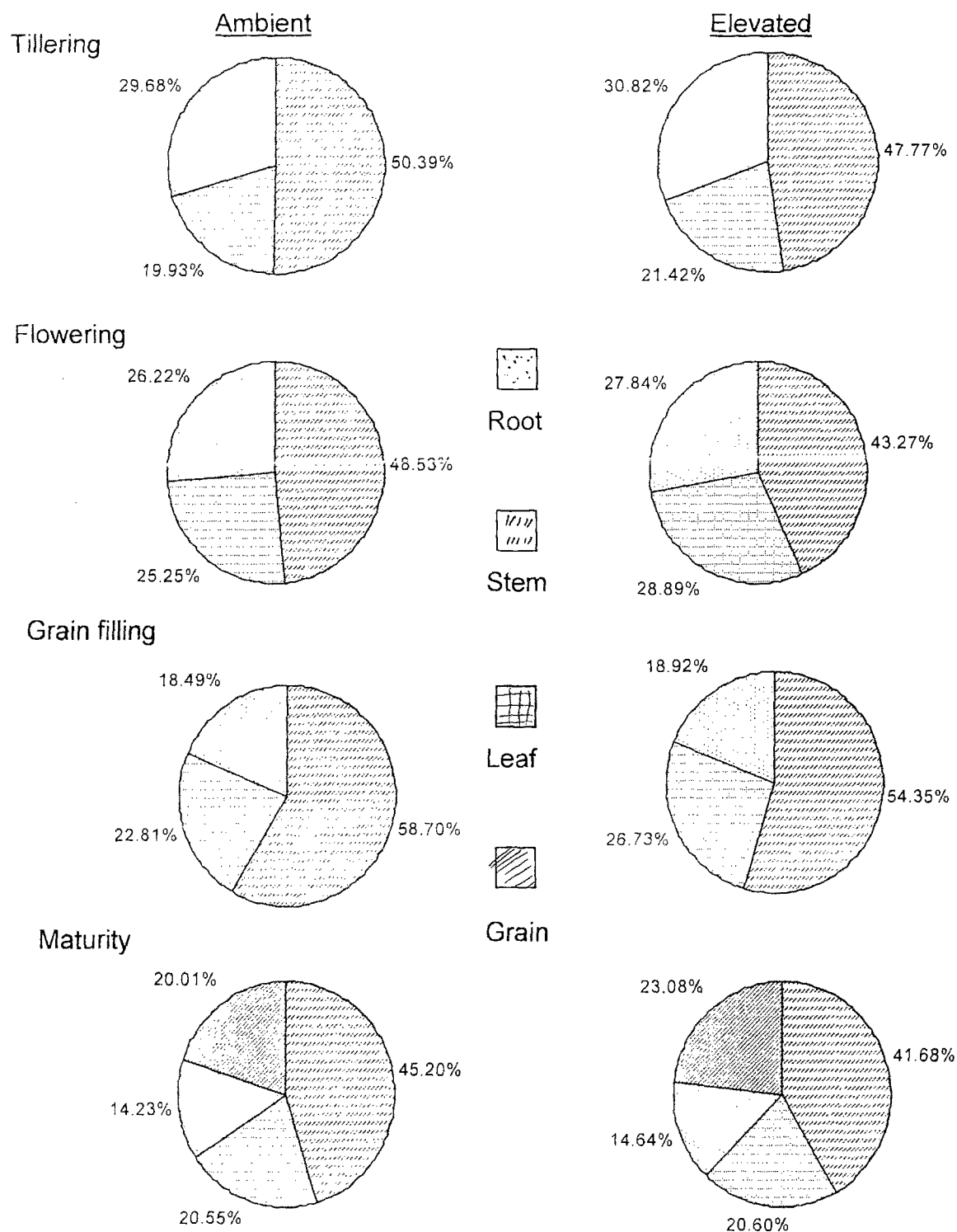
The differences between values with any common alphabet in figures are not statistically significant and *vice versa*

Table 9. Total dry matter yield (g pot⁻¹) of rice grown in OTC as influenced by the interaction of levels of CO₂ and stages of crop growth

Growth stages	Levels of CO ₂	
	Ambient	Elevated
Tillering	24.25 ^f	28.20 ^e
Flowering	65.18 ^d	88.37 ^b
Grain filling	69.61 ^c	90.73 ^b
Maturity	69.66 ^c	95.22 ^a

The differences between values with any common alphabet in table are not statistically significant and *vice versa*

Fig. 12. Biomass partitioning to different plant parts at various stages of rice grown in OTC as affected by elevation of atmospheric CO₂ concentration



initial phase of rice growth could be due to the increased rate of stem and leaf growth during initial vegetative phase; while the decline towards maturity is ascribed to the degradation of finer roots and photosynthetic translocation to grain. The decrease was maximum between flowering and grain filling stages because of the decay of roots occurring during this period. Irrespective of the levels of CO₂, biomass partitioning to leaves remained more or less similar throughout the crop growth. Partitioning towards stem decreased as the crop progressed from tillering to flowering, increased further at grain filling stage and later decreased towards maturity due to the translocation of photosynthates to grain.

Biomass distribution pattern at four physiological stages of rice crop were quite different under ambient and elevated CO₂ concentrations. Interestingly, at all four stages of rice growth the per cent biomass allocation belowground to root was higher under elevated CO₂. Similarly an increased partitioning of dry matter to leaves was also observed under elevated CO₂ condition. However, the partitioning towards stem was lower under elevated CO₂ concentration probably due to the increased apportioning to roots and leaves. The per cent dry matter accumulation in grain increased slightly from 20.01 under ambient to 23.08 under elevated CO₂ thus establishing the positive role of elevation of atmospheric CO₂ in increasing harvest index of the crop.

f) Fresh root weight

The average values of fresh root weight of rice as functions of levels of CO₂ and stages of crop growth are presented in Figure 13. On an average, fresh root weight of rice was 46.44 g pot⁻¹ under ambient CO₂. Elevation of atmospheric CO₂ concentration increased its value to 62.84 g pot⁻¹, thus representing an increase of 35.31 per cent (Fig. 13a). As observed in case of root dry weight, fresh root weight increased up to flowering, and subsequently decreased towards maturity (Fig. 13b).

Interaction between levels of CO₂ and stages of rice growth had significant effect on fresh root weight and the values are presented in Table 10. Fresh root weight of rice was observed to be maximum at flowering stage under both CO₂ conditions. The values of fresh root weight under elevated

Fig. 13. Fresh root weight (g pot⁻¹) of rice grown in OTC as influenced by:

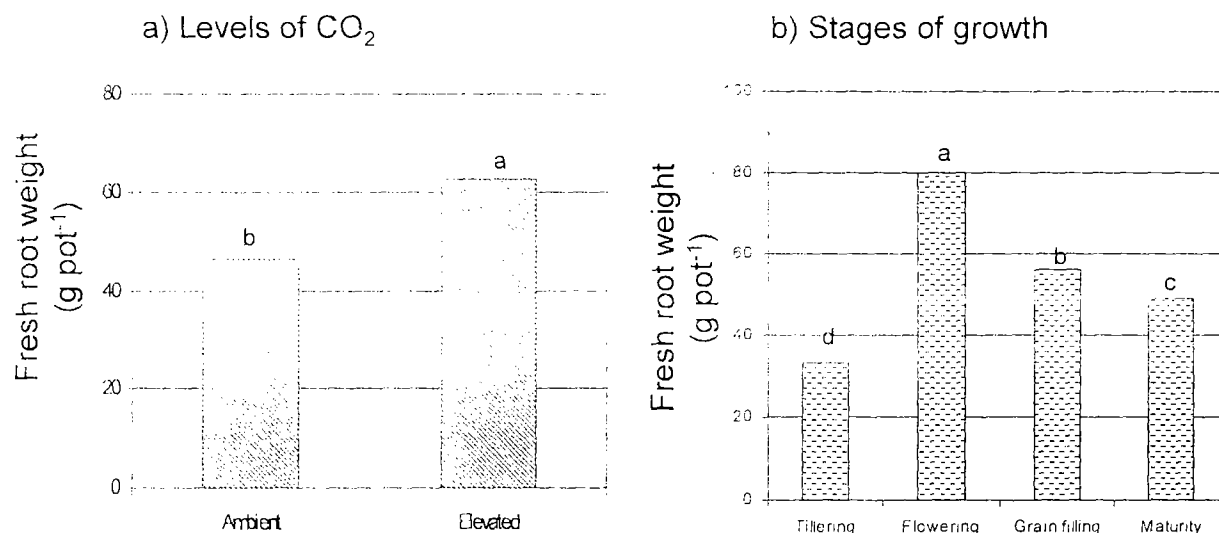


Table 10. Fresh root weight (g pot⁻¹) of rice grown in OTC as influenced by the interaction of levels of CO₂ and stages of crop growth

Growth stages	Levels of CO ₂	
	Ambient	Elevated
Tillering	28.10 ^f	38.03 ^e
Flowering	87.50 ^b	92.73 ^a
Grain filling	48.02 ^d	64.51 ^b
Maturity	42.15 ^{de}	56.09 ^c

The differences between values with any common alphabet in figures or table are not statistically significant and *vice versa*

CO₂ at different stages of rice growth were always significantly higher than the corresponding values under ambient CO₂ conditions. Irrespective of the levels of CO₂, fresh root weight increased up to flowering and decreased further towards maturity. But, under ambient CO₂, the decrease in fresh root weight between grain filling and maturity stages was not statistically significant. This further signifies the fact that the extent of root turn over and consequent incorporation of root mass to soil near maturity stage of the crop was more under elevated CO₂ than ambient condition.

g) Root volume

Values pertaining to root volume as affected by levels of CO₂ and stages of crop growth are presented in Figure 14. Treatments belonging to ambient CO₂ produced an average root volume of 50.17 ml pot⁻¹ while those belonging to elevated CO₂ had 68.51 ml pot⁻¹ volume, thus amounting to an increase of 36.56 per cent (Fig. 14a).

Regarding the stages of rice growth, volume of roots also exhibited the same trend as that of dry root weight (Fig. 14b). Its value increased up to flowering stage, and subsequently decreased towards maturity.

Interaction between levels of CO₂ and stages of rice growth was significant and the values are presented in Table 11. Highest root volume was observed at flowering stage under elevated CO₂ condition. The values of root volume under elevated CO₂ at all stages of rice growth were higher than the corresponding values under ambient CO₂ conditions. In both ambient and elevated OTCs, root volume increased up to flowering and thereafter decreased. Irrespective of the levels of CO₂, the decrease in root volume was maximum between flowering and grain filling stages, thus corroborating the trend obtained earlier while recording root dry weight. The decrease occurring between grain filling and maturity stages was insignificant under ambient CO₂.

B. Carbon and nitrogen uptake and its partitioning

a) Content and uptake of carbon by stem

The stem carbon contents as affected by levels of CO₂ and stages of crop growth are presented in Figure 15. The values of carbon uptake by stem dry matter of rice as functions of levels of CO₂ and stages of crop growth are presented in Figure 16. Exposure to enhanced CO₂ concentration did not

Fig. 14. Root volume (ml pot⁻¹) of rice grown in OTC as influenced by:

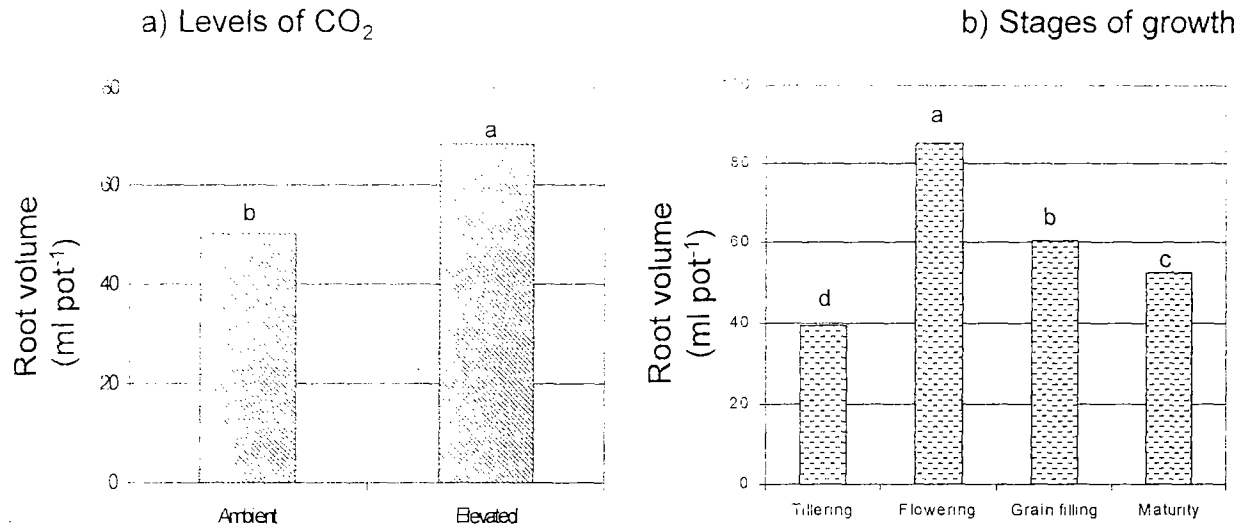


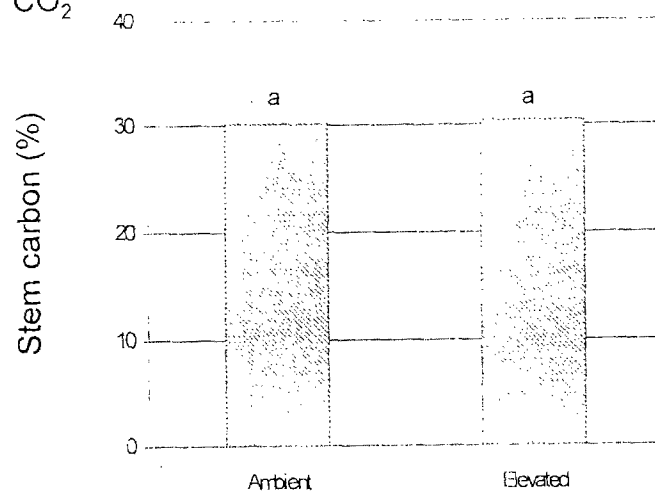
Table 11. Root volume (ml pot⁻¹) of rice grown in OTC as influenced by the interaction of levels of CO₂ and stages of crop growth

Growth stages	Levels of CO ₂	
	Ambient	Elevated
Tillering	33.24 ^e	45.36 ^d
Flowering	71.96 ^b	98.66 ^a
Grain filling	50.89 ^d	69.75 ^b
Maturity	44.58 ^d	60.27 ^c

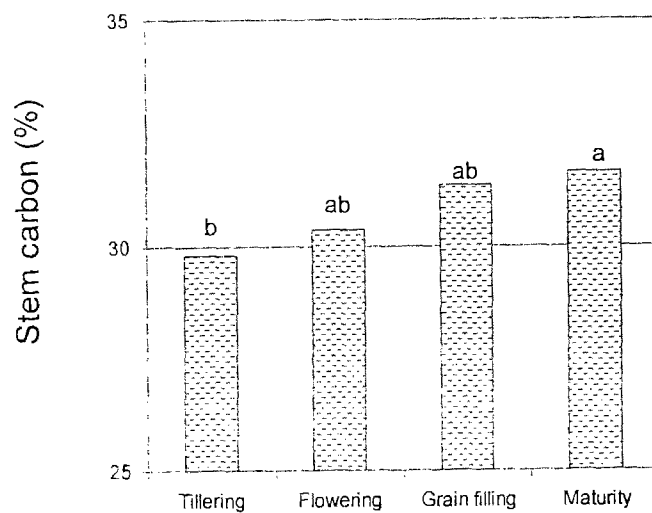
The differences between values with any common alphabet in figures or table are not statistically significant and *vice versa*

Fig. 15. Stem carbon concentration (per cent) in rice grown in OTC as influenced by

a) Levels of CO₂



b) Stages of growth



The differences between values with any common alphabet in figures are not statistically significant and *vice versa*

Fig. 16. Carbon uptake (mg pot^{-1}) by stem dry matter of rice grown in OTC as influenced by:

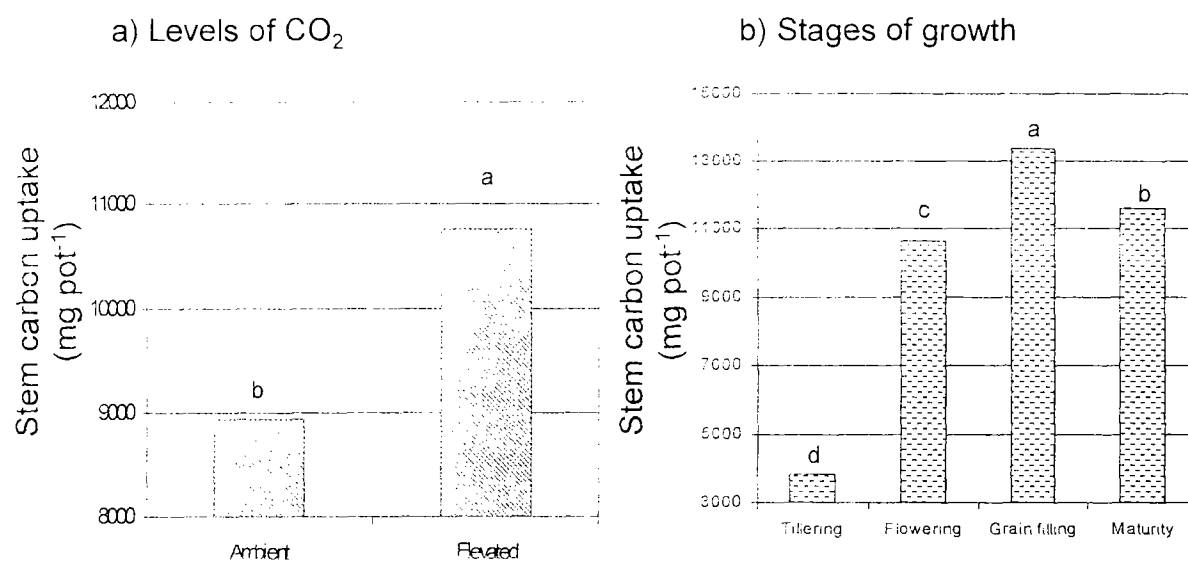


Table 12. Carbon uptake (mg pot^{-1}) by stem dry matter of rice grown in OTC as influenced by the interaction of levels of CO₂ and stages of crop growth

Growth stages	Levels of CO ₂	
	Ambient	Elevated
Tillering	3603 ^g	4056 ^f
Flowering	9576 ^e	11659 ^c
Grain filling	11985 ^b	14750 ^a
Maturity	10595 ^d	12592 ^b

The differences between values with any common alphabet in figures or table are not statistically significant and vice versa

have any significant effect on carbon content in stem (Fig. 15a). Given the fact that stem dry matter yield increased on exposure to elevated CO₂, average carbon uptake by stem dry matter increased by 20.09 per cent from 9.13 g pot⁻¹ under ambient to 10.97 g pot⁻¹ under elevated CO₂ concentration (Fig. 16a).

Stages of rice growth did not have any significant effect on stem carbon concentration except a slight increase towards maturity (Fig. 15b). Only tillering and maturity stages differed significantly with respect to stem C composition. However, the uptake of carbon by rice stem showed an increasing trend owing to the increase in biomass yield across the stages (Fig. 16b). As in case of stem dry matter yield, maximum stem C uptake was observed at grain filling and later decreased slightly, yet significantly, towards maturity.

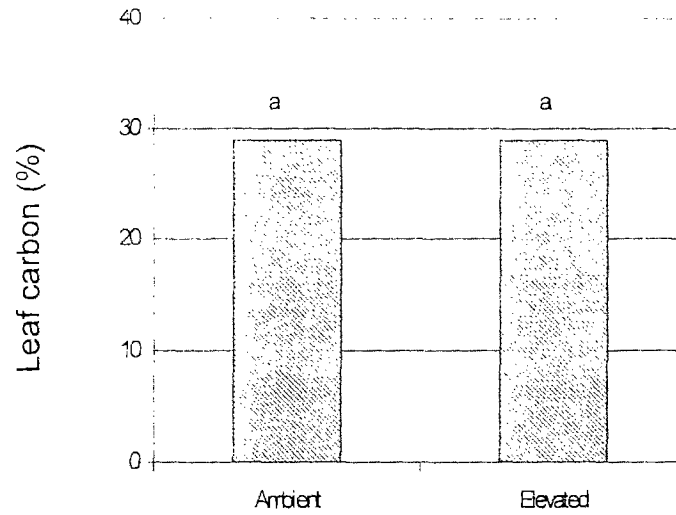
Interaction between levels of CO₂ and stages of rice growth influenced carbon uptake by stem, with highest carbon uptake associated with the grain filling stage of crop under elevated CO₂ (Table 12). At all stages of crop growth, uptake of C by rice stem was higher under elevated CO₂ over ambient condition. As stem dry matter yield exhibited a decreasing trend from grain filling to maturity (Fig. 7b), uptake of carbon also followed the same pattern in both elevated and ambient CO₂ conditions. However, the extent of decrease was higher under elevated CO₂, which indicates increased rate of translocation of photosynthates to the reproductive parts.

b) Content and uptake of carbon by leaves

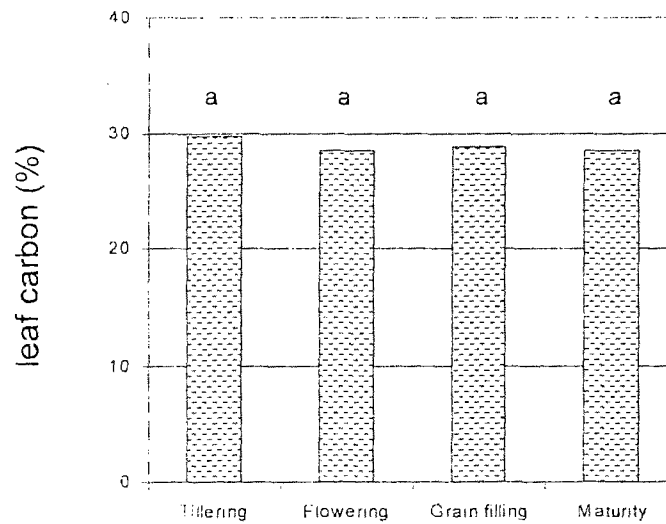
The average values of C concentration in leaves as functions of levels of CO₂ and stages of growth are presented in Figure 17. Elevation of CO₂ concentration in atmosphere did not have any significant effect on C content in leaves of rice (Fig. 17a). Carbon uptake by leaves as affected by CO₂ and stages of crop growth are presented in Figure 18. It was evident from Figure 18a that C uptake increased by 42.64 per cent in response to the elevation of CO₂ concentration in the atmosphere. As C composition remained unchanged under elevated CO₂, the corresponding gain in dry matter yield of leaf might have contributed to the increase in uptake values.

Fig. 17. Leaf carbon concentration (per cent) in rice grown in OTC as influenced by:

a) Levels of CO₂



b) Stages of growth



The differences between values with any common alphabet in figures are not statistically significant and *vice versa*

Fig. 18. Carbon uptake (mg pot^{-1}) by leaves of rice grown in OTC as influenced by:

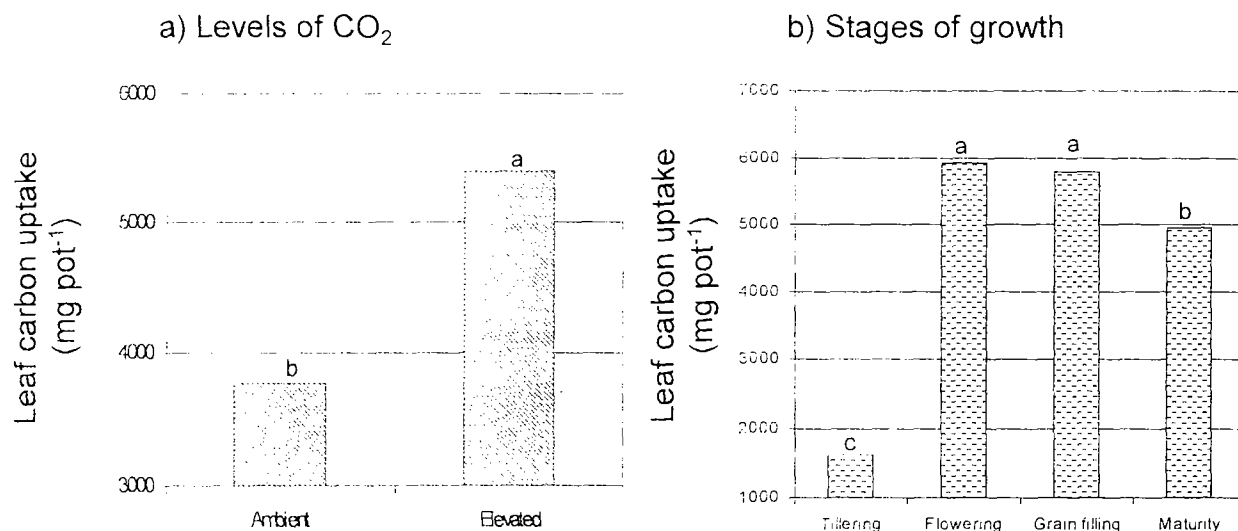


Table 13. Carbon uptake (mg pot^{-1}) by leaf dry matter of rice grown in OTC as influenced by the interaction of levels of CO₂ and stages of crop growth

Growth stages	Levels of CO ₂	
	Ambient	Elevated
Tillering	1440 ^d	1807 ^d
Flowering	4673 ^c	7278 ^a
Grain filling	4575 ^c	7014 ^a
Maturity	4399 ^c	5507 ^b

The differences between values with any common alphabet in figures or table are not statistically significant and *vice versa*

Carbon content in leaf did not change significantly with age of the crop either (Fig. 17b). The C uptake by rice leaves was very small in quantity at tillering, increased sharply as the crop matured to flowering, later remained unchanged up to grain filling and decreased towards maturity (Fig. 18b). A similar trend was observed in leaf dry matter as well (Fig. 8b).

Interaction between levels of CO₂ and growth stages was significant only in uptake values which are presented in Table 13. Under ambient CO₂, increase in C uptake by leaves was observed up to flowering and thereafter the changes were statistically insignificant. However, under elevated CO₂, increase in leaf C uptake was observed up to flowering, remained as such till grain filling and then decreased significantly towards maturity. C uptake by rice leaves was higher under elevated CO₂ at all stages of growth over the corresponding values under ambient condition.

c) Content and uptake of carbon by roots

The average carbon concentrations in roots as affected by elevation of CO₂ in atmosphere and the stages of crop growth are depicted in Figure 19. Elevation of atmospheric CO₂ concentration increased C content in rice roots from 33.17 to 37.46 per cent (Fig. 19a). Root C concentration was highest at tillering, decreased as crop progressed to flowering and then increased slightly at grain filling and remained unchanged till maturity (Fig. 19b). Keeping in view of the related data on root dry matter, which recorded maximum value at flowering stage of the crop, decrease in root C concentration at this stage looks merely to be dilution effect, which recovered later as the root weight decreased.

The values of carbon uptake by leaves as affected by CO₂ and stages of crop growth are presented in Figure 20. Elevation of atmospheric CO₂ concentration increased C uptake by rice roots from 3865 to 5597 mg pot⁻¹, thus amounting to 44.81 per cent gain (Fig. 20a).

Data pertaining to C uptake by rice roots followed the same trend as that of root dry matter with highest value observed at flowering stage in spite of the lowest value of C concentration at this stage (Fig. 20b). Root C uptake values decreased later with age of the crop.

Fig. 19. Root carbon concentration (per cent) in rice grown in OTC as influenced by:

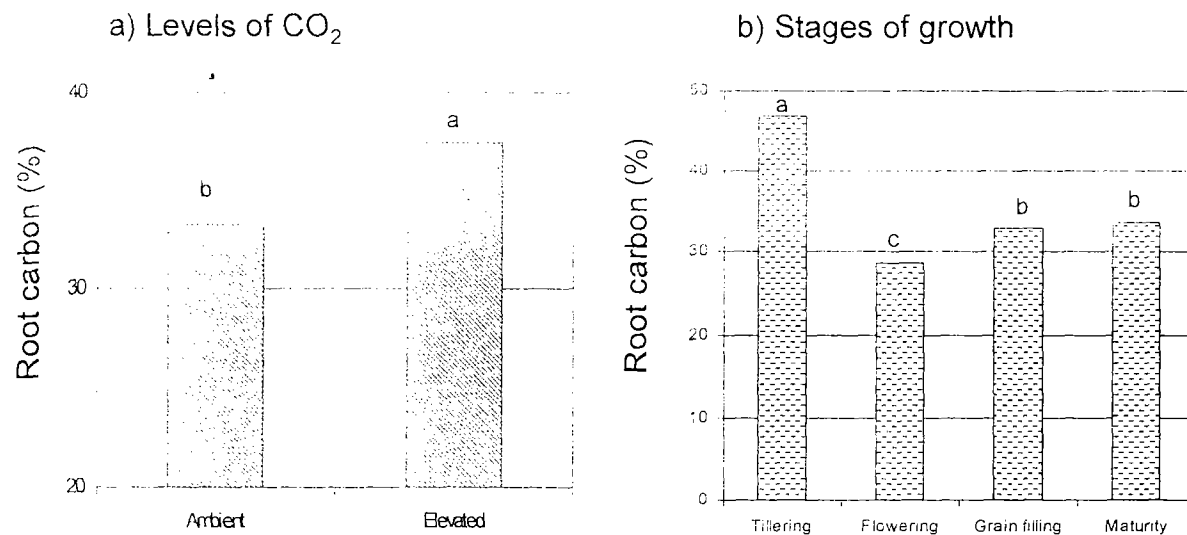


Table 14. Carbon concentration (per cent) in roots of rice grown in OTC as influenced by the interaction of levels of CO₂ and stages of crop growth

Growth stages	Levels of CO ₂	
	Ambient	Elevated
Tillering	42.25 ^b	51.53 ^a
Flowering	27.99 ^e	29.19 ^e
Grain filling	31.74 ^d	34.13 ^{cd}
Maturity	32.18 ^{cd}	34.98 ^c

The differences between values with any common alphabet in figures or table are not statistically significant and vice versa

Fig. 20. Carbon uptake (mg pot^{-1}) by roots of rice grown in OTC as influenced by:

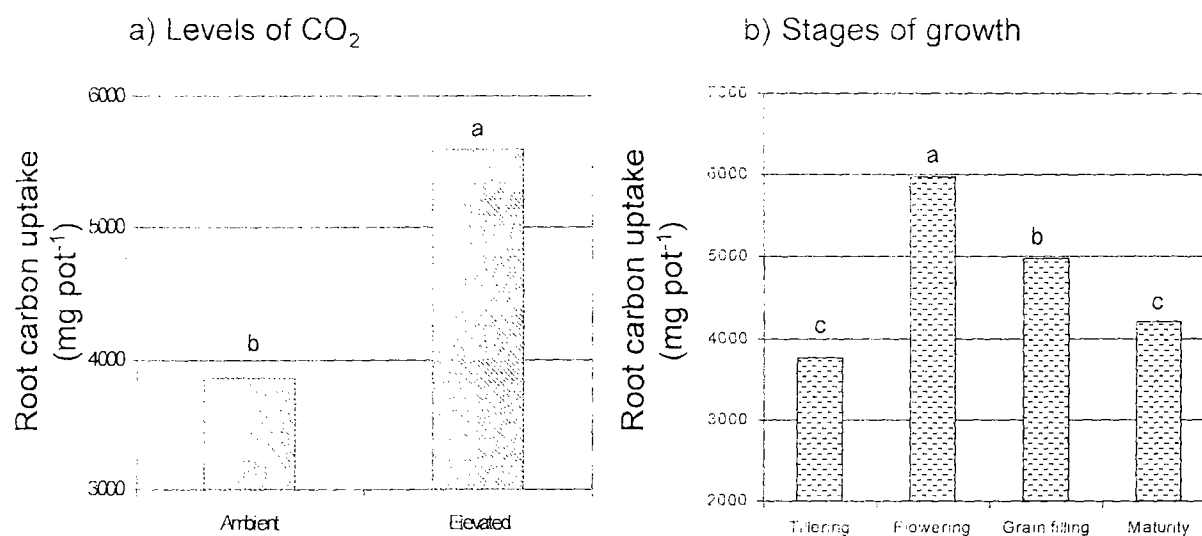


Table 15. Carbon uptake (mg pot^{-1}) by roots of rice grown in OTC as influenced by the interaction of levels of CO₂ and stages of crop growth

Growth stages	Levels of CO ₂	
	Ambient	Elevated
Tillering	3041 ^f	4478 ^{cd}
Flowering	4782 ^c	7171 ^a
Grain filling	4082 ^{de}	5863 ^b
Maturity	3553 ^{ef}	4878 ^c

The differences between values with any common alphabet in figures or table are not statistically significant and vice versa

Fig. 21. Carbon concentration (per cent) in the grains of rice grown in OTC as influenced by the elevation of atmospheric CO₂ concentration

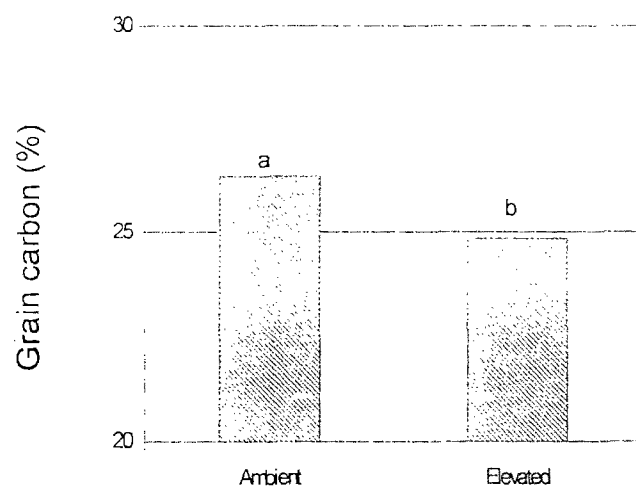
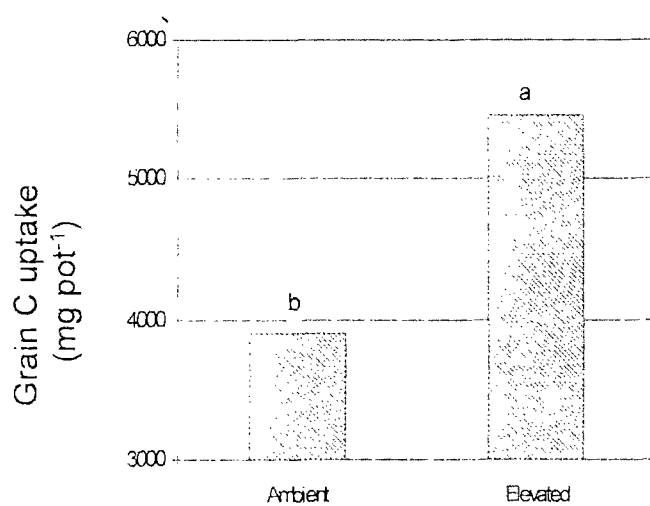


Fig. 22. Carbon uptake (mg pot⁻¹) by the grains of rice grown in OTC as influenced by the elevation of atmospheric CO₂ concentration



The differences between values with any common alphabet in figures are not statistically significant and *vice versa*

The two-way interaction had significant effect on both root C concentration and uptake and the values are presented in Tables 14 and 15, respectively. The C uptake by rice roots was observed to be highest at flowering under elevated CO₂. All the four stages of rice growth experienced significant gain in root C uptake under elevated atmospheric CO₂ when compared with the corresponding values under ambient CO₂.

d) Content and uptake of carbon by grains

Carbon content and its uptake by rice grains as a function of levels of CO₂ are given in Figures 21 and 22, respectively. Eventhough elevation of atmospheric CO₂ concentration brought about a decrease in C composition of rice grains; the uptake was augmented owing to the increase in dry weight.

e) Total carbon uptake and its partitioning

Total carbon uptake by rice as functions of levels of CO₂ and stages of growth are given in Figure 23. As a result of elevation of atmospheric CO₂ concentration, total carbon uptake by rice increased by 33.83 per cent over a value of 17.28 g pot⁻¹ (Fig. 23a). With age of the crop, plant carbon uptake exhibited an increasing trend (Fig. 23b). The increase was sharper between tillering and flowering stages due to faster rate of accumulation of photosynthates during this phase. The value further increased with age till maturity.

Interaction between levels of CO₂ and stages of crop growth was significant and the values are presented in Table 16. Carbon uptake by rice increased gradually till maturity under both ambient and elevated CO₂ concentrations. The positive effect of CO₂ was visible at all stages of rice growth.

Pattern of carbon partitioning to different plant parts at four physiological stages of rice under ambient and elevated CO₂ were different, and are presented in Figure 24. At all crop growth stages, exposure to higher CO₂ increased the preferential partitioning of carbon to roots. As a result, per cent carbon allocated below ground increased from 37.62 to 43.30 per cent at tillering stage of rice growth while the corresponding increases were from 25.12 to 27.47, 19.78 to 21.43 and 15.6 to 17.15 at flowering, grain filling and maturity, respectively. Preferential partitioning of photosynthates to stem was

Fig. 23. Total carbon uptake (mg pot^{-1}) by rice grown in OTC as influenced by:

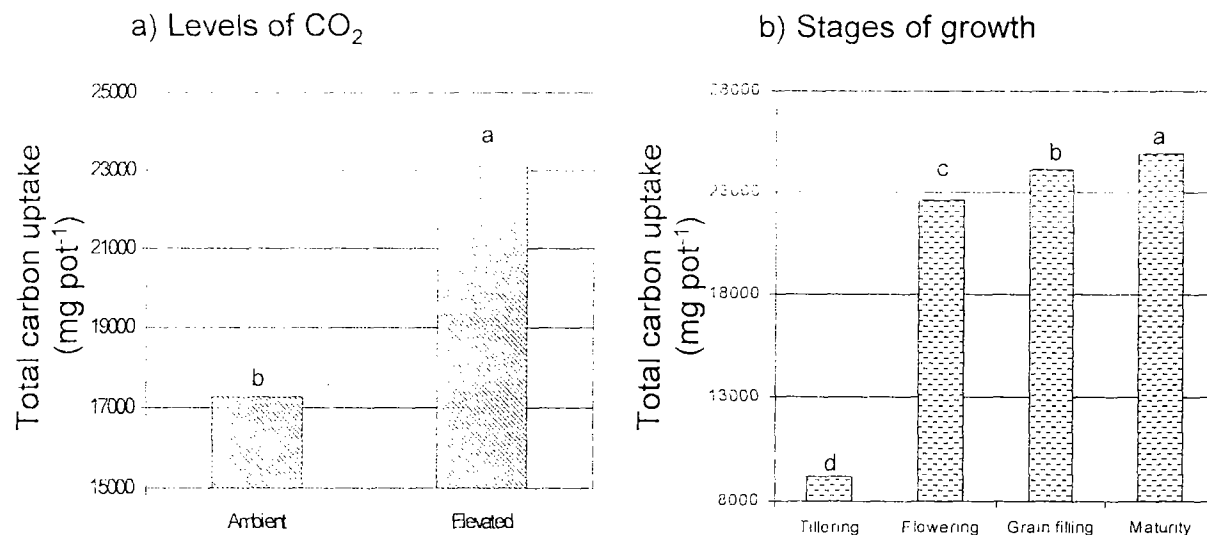
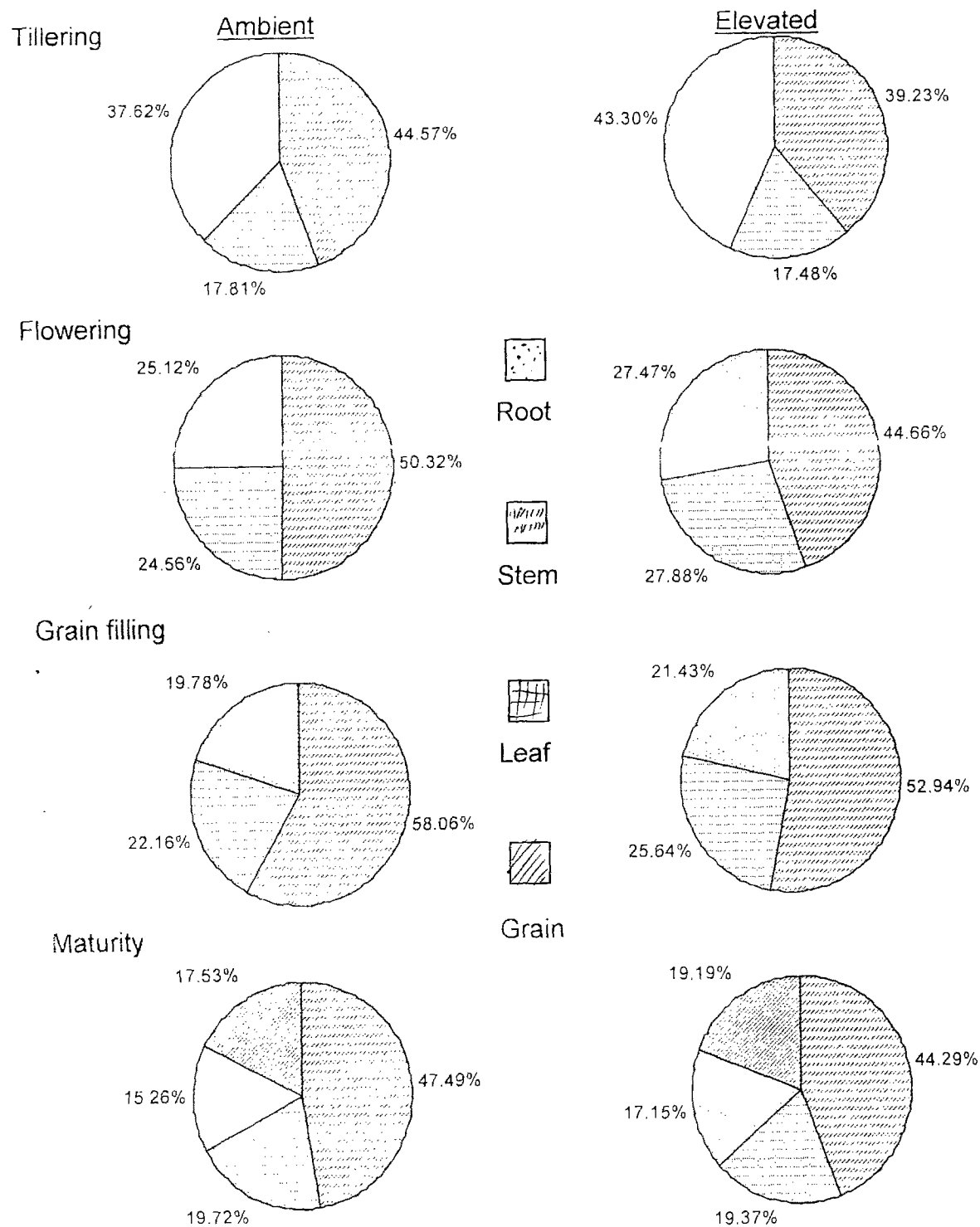


Table 16. Total carbon uptake (mg pot^{-1}) by rice grown in OTC as influenced by the interaction of levels of CO₂ and stages of crop growth

Growth stages	Levels of CO ₂	
	Ambient	Elevated
Tillering	8080 ^h	10341 ^g
Flowering	19031 ^f	26116 ^c
Grain filling	20634 ^e	27627 ^b
Maturity	21384 ^d	28430 ^a

The differences between values with any common alphabet in figures or table are not statistically significant and *vice versa*

Fig. 24. Carbon partitioning to different plant parts at various stages of rice grown in OTC as affected by elevation of atmospheric CO₂ concentration



higher under ambient CO₂ while the apportioning towards leaf dry matter was generally higher under elevated CO₂ excepting tillering and maturity stages. The per cent allocation of C to grains increased from 17.53 to 19.19 as a result of elevation of CO₂ concentration in atmosphere.

With age of the crop, carbon partitioning to roots decreased continuously, irrespective of the levels of CO₂. Preferential portioning of C to stem and leaves of rice initially increased and then decreased (in their per cent values) under both ambient and elevated CO₂ concentrations.

f) Nitrogen content and C:N ratio of stem dry matter

The per cent nitrogen content and C:N ratio of the stem dry matter of rice as individual functions of levels of CO₂ and stages of crop growth are presented in Figures 25 and 26, respectively. Elevation of atmospheric CO₂ significantly reduced the N concentration in rice stem (Fig. 25a). The N content in stem decreased significantly with age of the crop as well (Fig. 25b). However, C:N ratio of stem was not affected by higher CO₂ concentration in the atmosphere (Fig. 26a). As a result of the decrease in N content with age, C:N ratio was found to increase significantly towards maturity (Fig. 26b).

g) Nitrogen content and C:N ratio of leaves

The values pertaining to per cent nitrogen content and C:N ratio of rice leaves as affected by levels of CO₂ and stages of crop growth are presented in Figures 27 and 28, respectively. Elevation of atmospheric CO₂ concentration decreased the N concentration significantly by more than five per cent from 1.468 per cent under ambient CO₂ (Fig. 27a). With age of the crop, leaf N concentration also decreased significantly (Fig. 27b). Nevertheless, like stem, leaf C:N ratio was not affected by higher CO₂ concentration in the atmosphere (Fig. 28a). As a result of the decrease in N content with age, leaf C:N ratio was found to increase significantly towards maturity (Fig. 28b).

h) Nitrogen content and C:N ratio of root dry matter

The values pertaining to per cent nitrogen content and C:N ratio of rice roots as affected by levels of CO₂ and stages of crop growth are presented in Figures 29 and 30, respectively. Unlike stem and leaf, the root composition in terms of N concentration did not change significantly as a result of elevation of

Fig. 25. Nitrogen concentration (per cent) in stem dry matter of rice grown in OTC as influenced by:

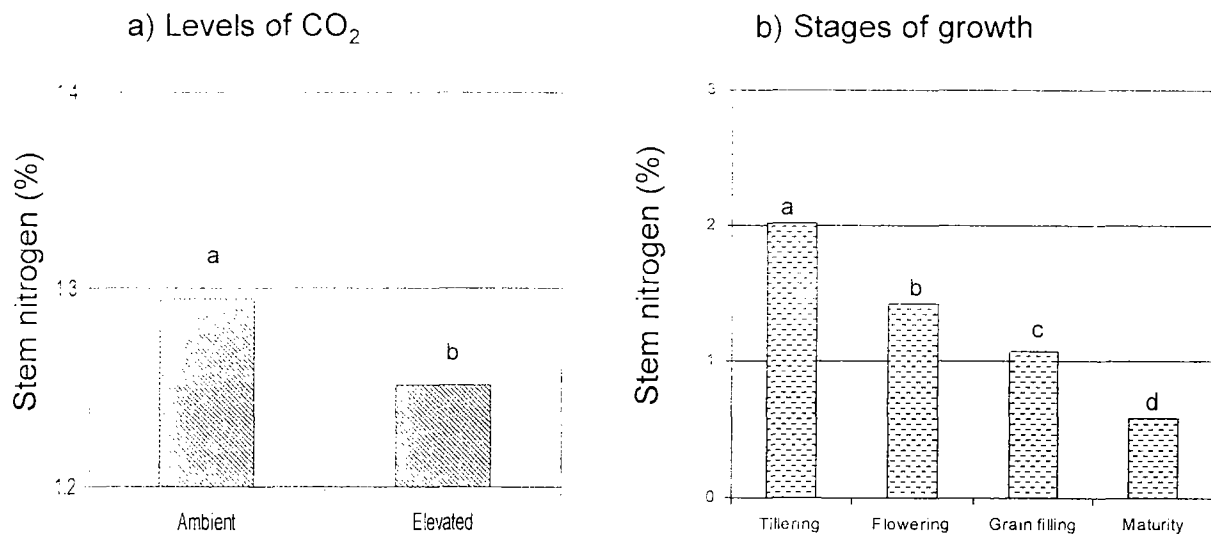
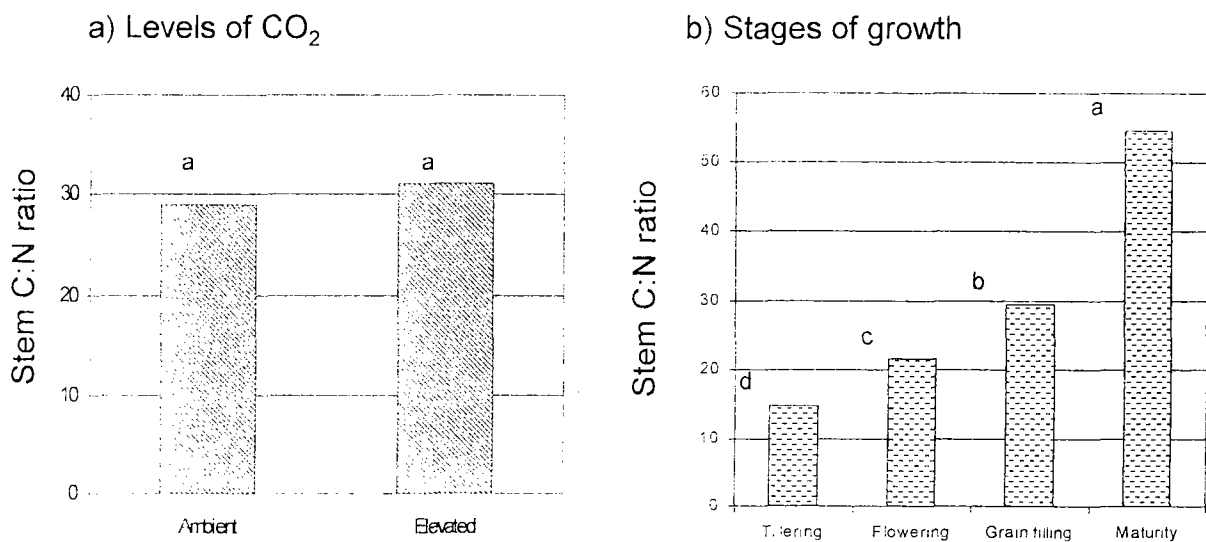


Fig. 26. The C:N ratio of stem dry matter of rice grown in OTC as influenced by:



The differences between values with any common alphabet in figures are not statistically significant and vice versa

Fig. 27. Nitrogen concentration (per cent) in leaves of rice grown in OTC as influenced by:

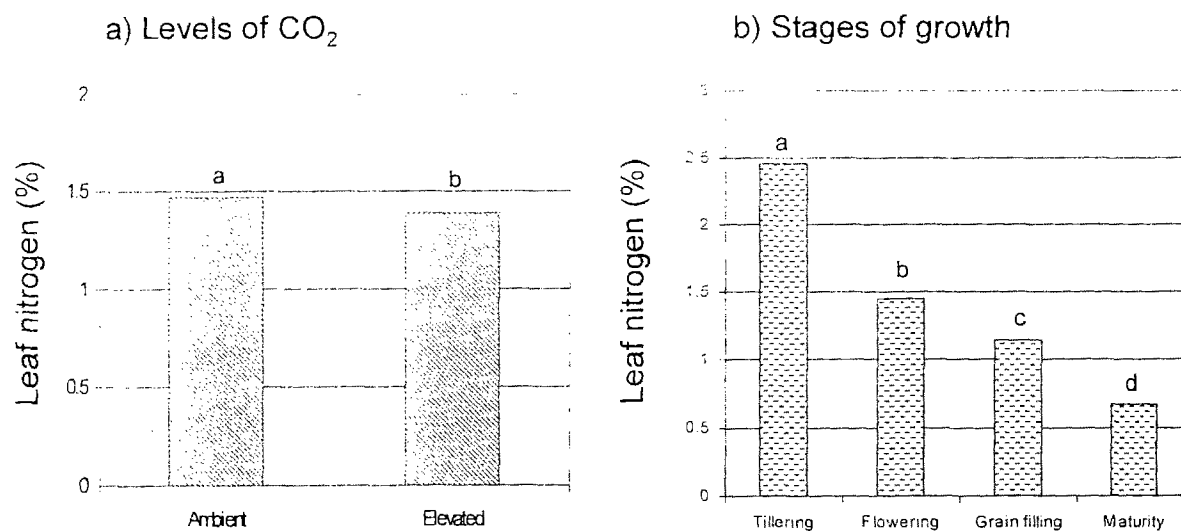
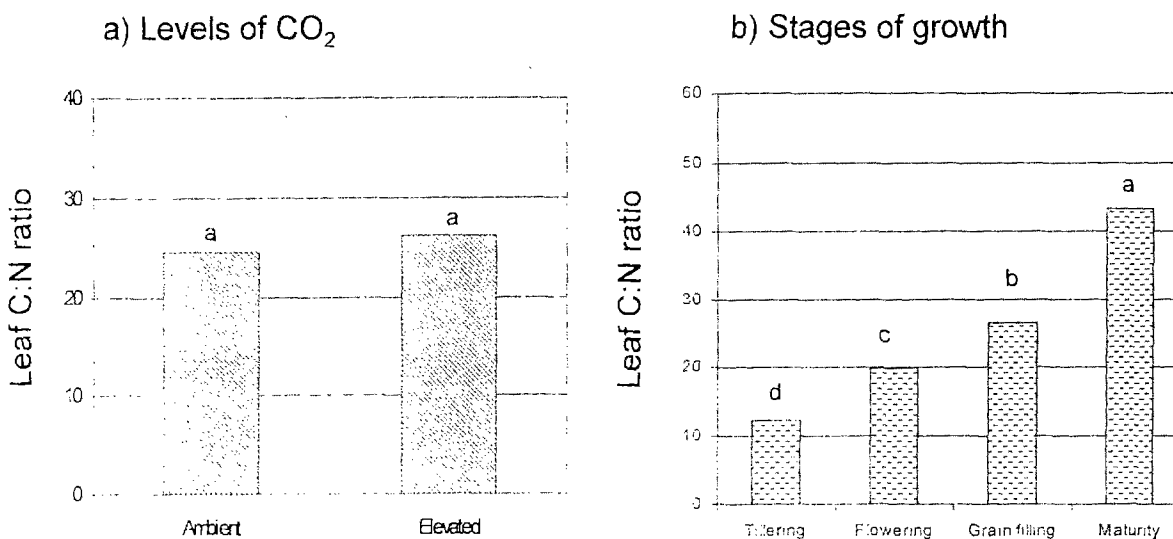


Fig. 28. The C:N ratio of leaf dry matter of rice grown in OTC as influenced by:



The differences between values with any common alphabet in figures are not statistically significant and *vice versa*

Fig. 29. Nitrogen concentration (per cent) in roots of rice grown in OTC as influenced by:

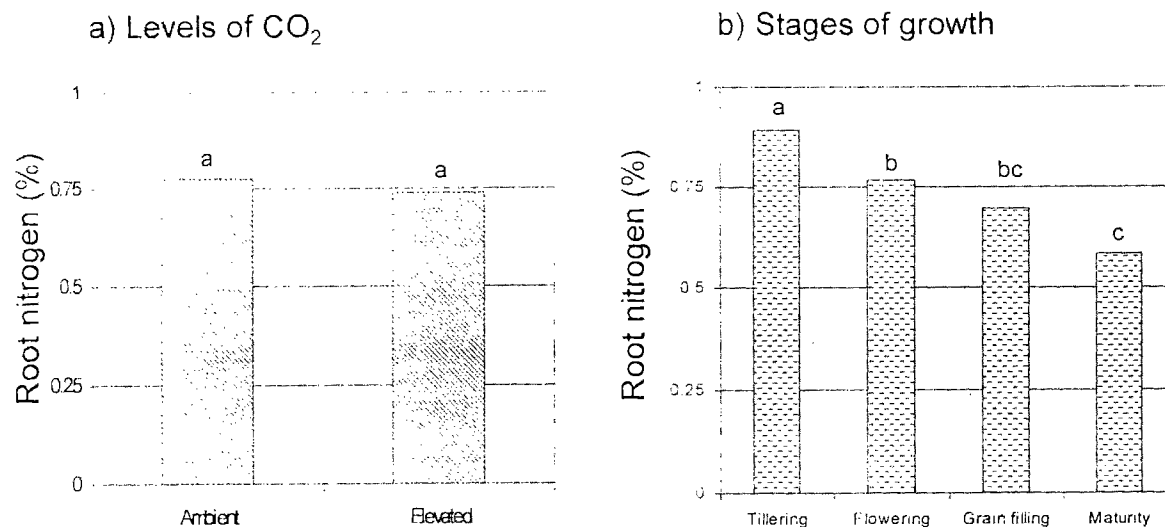
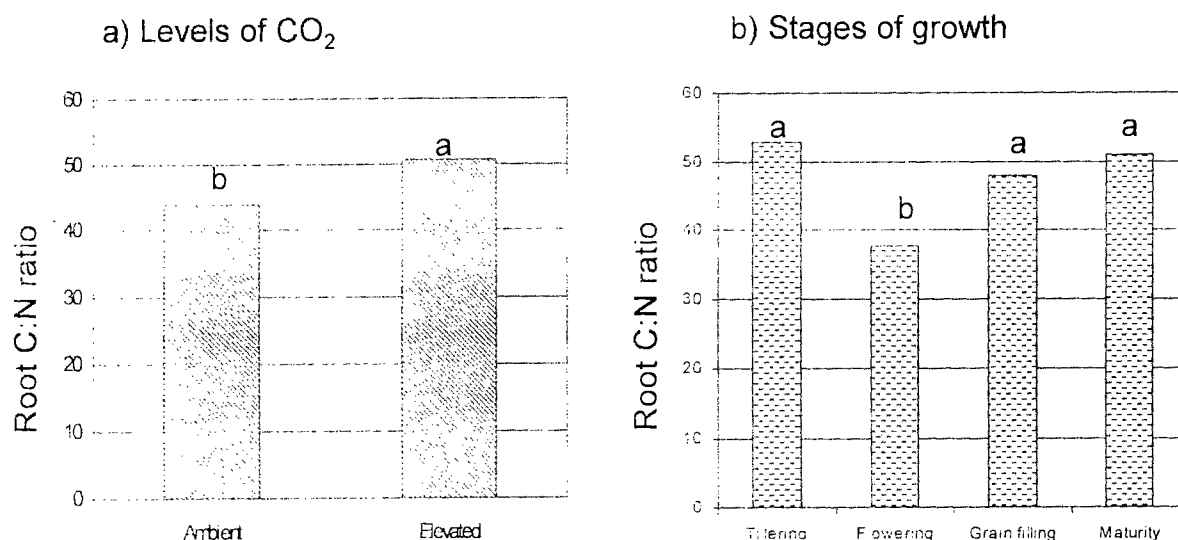


Fig. 30. The C:N ratio of roots of rice grown in OTC as influenced by:



The differences between values with any common alphabet in figures are not statistically significant and vice versa

CO₂ concentration in atmosphere (Fig. 29a). However, its value decreased significantly when the crop matured from tillering to flowering, and thereafter decreased towards maturity (Fig. 29b). However, there was no significant difference in root N content between flowering and grain filling as well as between grain filling and maturity stages. As a result of the increase in C content in roots (Fig. 19a), C:N ratio was found to increase significantly from 43.93 under ambient to 50.7 under elevated CO₂ concentration (Fig. 30a). As the crop progressed from tillering to flowering, root C:N ratio decreased significantly due to the abrupt decrease in C concentration in roots between these stages (Fig. 30b). Later, an increase in C:N ratio was observed as C and N composition of rice roots changed in opposite direction.

i) Nitrogen content and C:N ratio of grains

The values pertaining to per cent nitrogen composition and C:N ratio of rice grains as affected by levels of CO₂ are presented in Figures 31 and 32, respectively. The N concentration decreased significantly as a result of elevation of CO₂ concentration in the atmosphere. However the C:N ratio remained unchanged in rice grains due to change in atmospheric CO₂ concentration (Fig. 32).

4.1.1.2 Soil parameters

A. Carbon pools

a) Microbial biomass carbon (MBC)

Microbial biomass carbon having high turnover rate is one of the dynamic and labile phases of soil carbon. The average value of MBC in rice rhizosphere as affected by the levels of CO₂ and stages of growth are given in the Figure 33. As a result of elevation of atmospheric CO₂, an increase in MBC content by 40.70 per cent was recorded in rice rhizosphere soil (Fig. 33a).

The amount of MBC in rice rhizosphere was observed to be maximum at tillering stage (Fig. 33b). MBC remained quite high till flowering and later as the crop approached maturity an abrupt decrease in MBC content was observed in rhizosphere soil. The higher values of MBC in rice rhizosphere during the initial period of crop growth might be due to more secretions by immature root cells. After flowering, crop enters the reproductive phase and

Fig. 31. Nitrogen concentration (per cent) in the grains of rice grown in OTC as influenced by the elevation of atmospheric CO₂ concentration

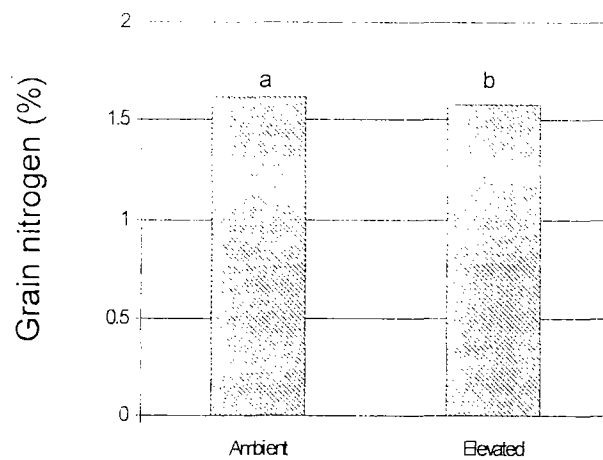
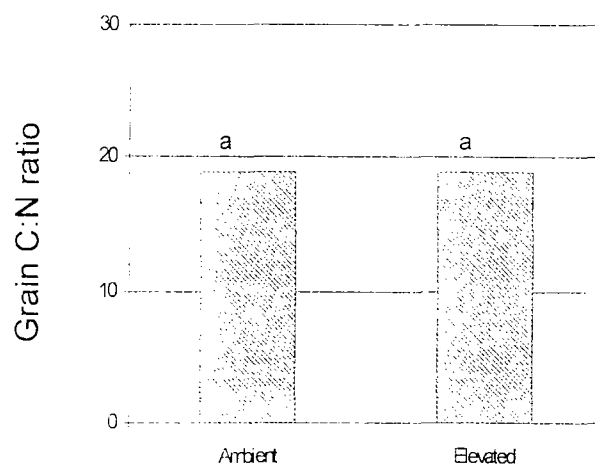


Fig. 32. The C:N ratio of the grains of rice grown in OTC as influenced by the elevation of atmospheric CO₂ concentration



The differences between values with any common alphabet in figures are not statistically significant and *vice versa*

Fig.33. Microbial biomass carbon (MBC, mg kg⁻¹) in rice rhizosphere at OTC as influenced by:

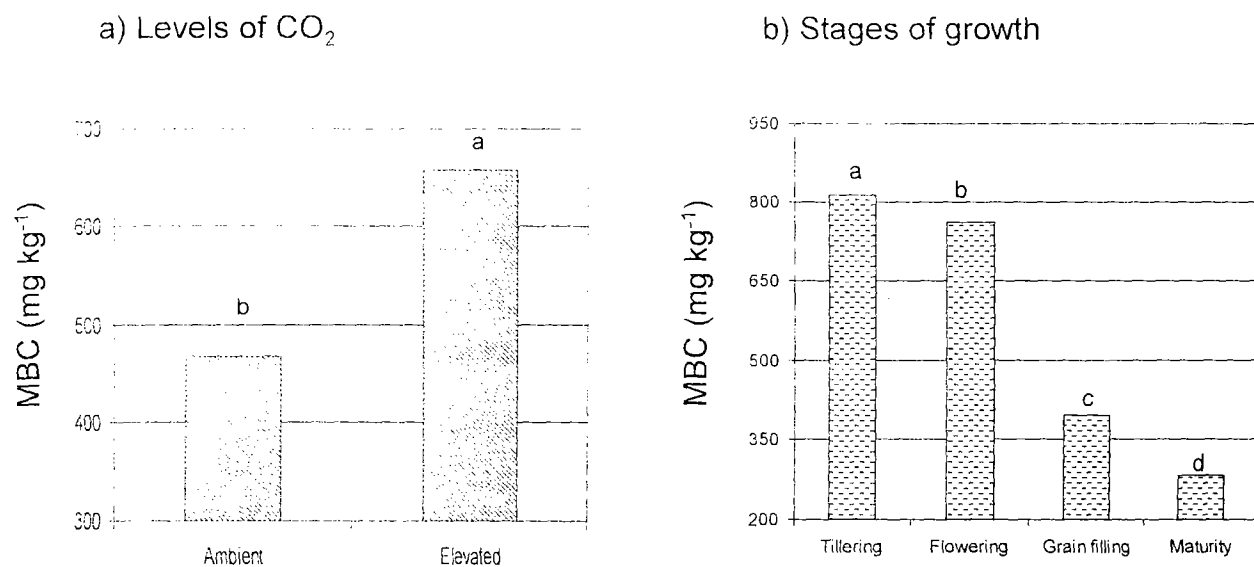


Table 17. Microbial biomass carbon (MBC, mg kg⁻¹) in rice rhizosphere at OTC as influenced by the interaction of levels of CO₂ and stages of crop growth

Growth stages	Levels of CO ₂	
	Ambient	Elevated
Tillering	688.0 ^b	939.6 ^a
Flowering	617.7 ^c	905.3 ^a
Grain filling	326.0 ^e	463.5 ^d
Maturity	238.7 ^f	323.1 ^e

The differences between values with any common alphabet in figures or table are not statistically significant and *vice versa*

there is decrease in root activity following the decay of roots in rhizosphere, resulting into a decrease in microbial biomass. Moreover, preferential translocation of photosynthates to the reproductive parts towards maturity might also have reduced the exudation by roots at that stage leading to a fall in rhizosphere effect. The decreased influence of crop rhizosphere can reduce microbial counts and hence MBC might be expected to decrease near maturity.

Interaction between levels of CO₂ and stages of growth was significant and is presented in Table 17. While under ambient CO₂, the MBC values decreased from tillering to flowering, these two stages were at par under elevated CO₂. At all stages of rice growth, MBC contents under elevated CO₂ were higher than the corresponding values under ambient CO₂. It is interesting to note that MBC content in soil at tillering under ambient CO₂ was lower than the value recorded even at flowering stage under elevated CO₂.

b) Dissolved organic carbon (DOC)

Dissolved organic carbon refers to the low molecular weight carbon compounds generally associated with root exudates and their decomposition products. Average values of DOC as functions of levels of CO₂ and stages of crop growth are recorded in Figure 34. Elevation of atmospheric CO₂ from 372 to 600 $\mu\text{mol mol}^{-1}$ has caused an increase in DOC by 17.4 per cent (Fig. 34a) as the absolute value increased from 112.39 mg kg⁻¹ under ambient to 130.97 mg kg⁻¹ under elevated CO₂. This increase in DOC can clearly be linked to the increasing biomass and carbon partitioning to the underground portions of the crop as described earlier. Higher root growth under elevated CO₂ condition might have enhanced the secretion and exudation which in turn, might have augmented the DOC content in rhizosphere.

With relation to growth stages, the DOC content was observed to be maximum at tillering with a sharp drop at flowering stage followed by gradual decrease towards maturity (Fig. 34b). During initial period of rice growth, root cells would be devoid of secondary cell walls and there would be more probability of leakage and exudation of carbonaceous substances, thus boosting up DOC content in rhizosphere soil.

Fig. 34. Dissolved organic carbon (DOC, mg kg⁻¹) in rice rhizosphere at OTC as influenced by :

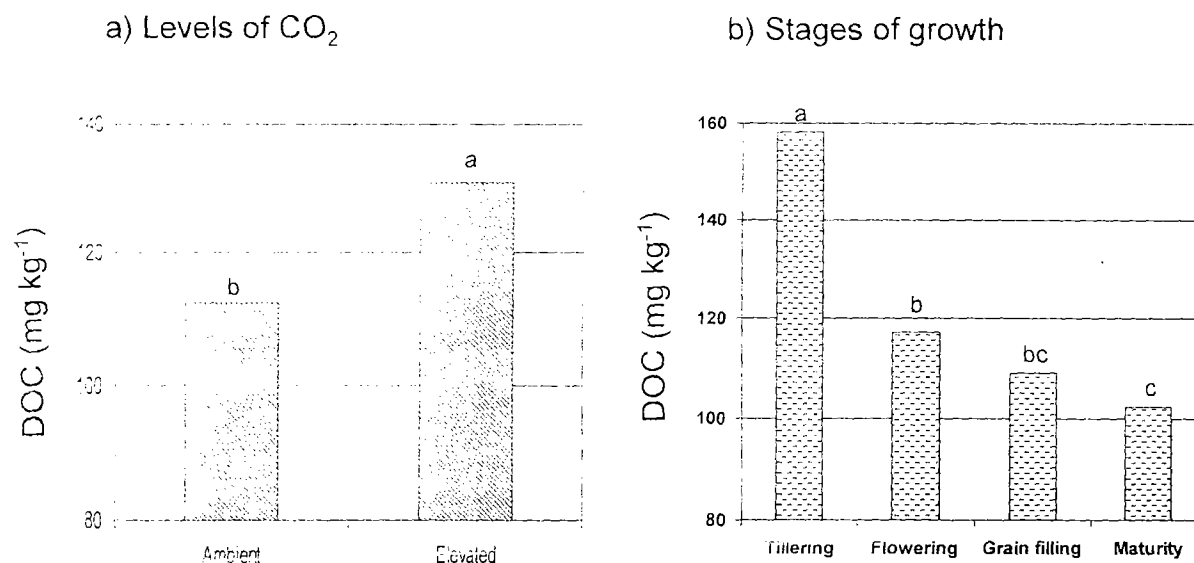


Table 18. Dissolved organic carbon (DOC, mg kg⁻¹) in rice rhizosphere at OTC as influenced by the interaction of levels of CO₂ and stages of crop growth

Growth stages	Levels of CO ₂	
	Ambient	Elevated
Tillering	146.6 ^b	169.7 ^a
Flowering	110.2 ^{de}	124.2 ^c
Grain filling	99.00 ^{ef}	119.1 ^{cd}
Maturity	93.84 ^f	110.9 ^{cde}

The differences between values with any common alphabet in figures or table are not statistically significant and vice versa

Interaction between levels of CO₂ and stages of rice growth was also significant and the values are shown in Table 18. Highest DOC in rice rhizosphere was observed at tillering under elevated CO₂ condition. This was followed by the value at tillering under ambient CO₂. Irrespective of the CO₂ levels, the DOC contents decreased sharply from tillering to flowering stage. After flowering stage, though there was a general decline in DOC values till maturity, such a trend was more significant under ambient CO₂ than under elevated CO₂. At all stages of crop growth, the DOC contents were higher under elevated CO₂ in comparison to the corresponding values under ambient CO₂.

c) Carbohydrate carbon (CHC)

Carbohydrate carbon is the organic carbon fraction having the polyhydroxy structure that is contributed mainly by structural carbohydrates of root cells released upon their lysis. Besides, secretion and exudation by roots also become a part of the carbohydrate pool in soil. The average effects of CO₂ and growth stages on CHC content in rice rhizosphere soil are depicted in Figure 35. As the level of CO₂ increased, an increase in average CHC content by 9.07 per cent was observed in rice rhizosphere soil (Fig. 35a). The CO₂ stimulated increase in biomass, root growth and translocation of biomass to underground portions might have contributed to the increased values of CHC under high CO₂.

With regard to stages of growth, average CHC content was lowest at tillering stage (1678 mg kg⁻¹) and gradually increased to 3008 mg kg⁻¹ as the crop approached maturity (Fig. 35b). The CHC contents in rice rhizosphere were at par between grain filling and maturity stages. An abrupt increase in CHC value observed in between flowering and grain filling stages might be due to the lysis of finer root cells leading to release of structural carbohydrates. It might be recalled that loss of root dry weight between these two stages was also highest, thus supporting this hypothesis.

Interaction had significant influence on CHC content in rice rhizosphere with higher values being associated with elevated CO₂ treatment at all stages of growth (Table 19). Highest CHC content (3181 mg kg⁻¹) in rhizosphere soil was observed at maturity stage of rice under elevated CO₂. This was followed

Fig. 35. Carbohydrate carbon (CHC, mg kg⁻¹) in rice rhizosphere at OTC as influenced by:

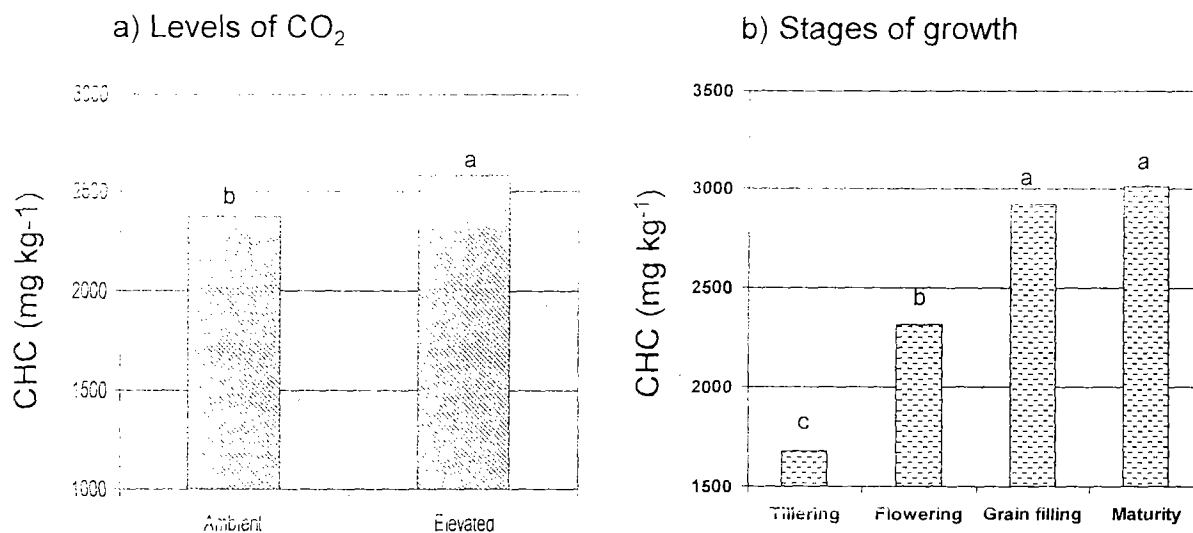


Table 19. Carbohydrate carbon (CHC, mg kg⁻¹) in rice rhizosphere at OTC as influenced by the interaction of levels of CO₂ and stages of crop growth

Growth stages	Levels of CO ₂	
	Ambient	Elevated
Tillering	1627 ^g	1728 ^f
Flowering	2251 ^e	2375 ^d
Grain filling	2771 ^c	3059 ^b
Maturity	2834 ^c	3181 ^a

The differences between values with any common alphabet in figures or table are not statistically significant and vice versa

in succession by the content at grain filling stage under elevated CO₂ and those at maturity and grain filling stages under ambient CO₂. It is very interesting to note that the difference between CHC values under elevated and ambient CO₂ conditions got widened as the crop approached maturity. This reiterates the fact that the primary source of gain in CHC pool in response to the elevation of CO₂ is the increased decay and lysis of the profuse root system prevailing in that situation.

d) Labile carbon (LBC)

Labile carbon (LBC) represents the pool of soil carbon that is oxidized by 0.333 M KMnO₄ (Blair *et al.*, 1995). The LBC contents in rice rhizosphere soil as influenced by the levels of CO₂ and stages of rice growth are depicted in Figure 36. Elevation of atmospheric CO₂ concentration increased LBC contents in rice rhizosphere soil by 6.78 per cent as the value increased from 1917 at ambient to 2047 mg kg⁻¹ (Fig. 36a).

The LBC is generally comprised of the relatively resistant (than the previously discussed pools) yet soluble and easily oxidisable fraction of soil carbon. It consists of certain fractions of DOC, CHC and MBC in soil. As the crop progressed from tillering to maturity, there was an increase in LBC content in rhizosphere soil. The highest value was associated with the maturity stage and the lowest with tillering (Fig. 36b). All four physiological stages differed significantly with respect to LBC contents in rice rhizosphere soil. The increase in LBC contents in soil from tillering to flowering can be attributed to the augmented contribution from DOC, as root activity and exudation of organic substances from roots gets boosted up during this stage. The elevation in the values of LBC towards maturity can be explained by lysis and degradation of root mass, thus adding high molecular weight compounds to this pool.

Interaction effect was significant with higher values of LBC in rhizosphere soil under elevated CO₂ at all stages of rice growth (Table 20). With age of the crop, there was a continuous and significant increase in LBC content under ambient CO₂, while under elevated CO₂ the increase was recorded till grain filling stage only. The values at grain filling and maturity stages were not significantly different.

Fig. 36. Labile carbon contents (LBC, mg kg⁻¹) in rice rhizosphere at OTC as influenced by :

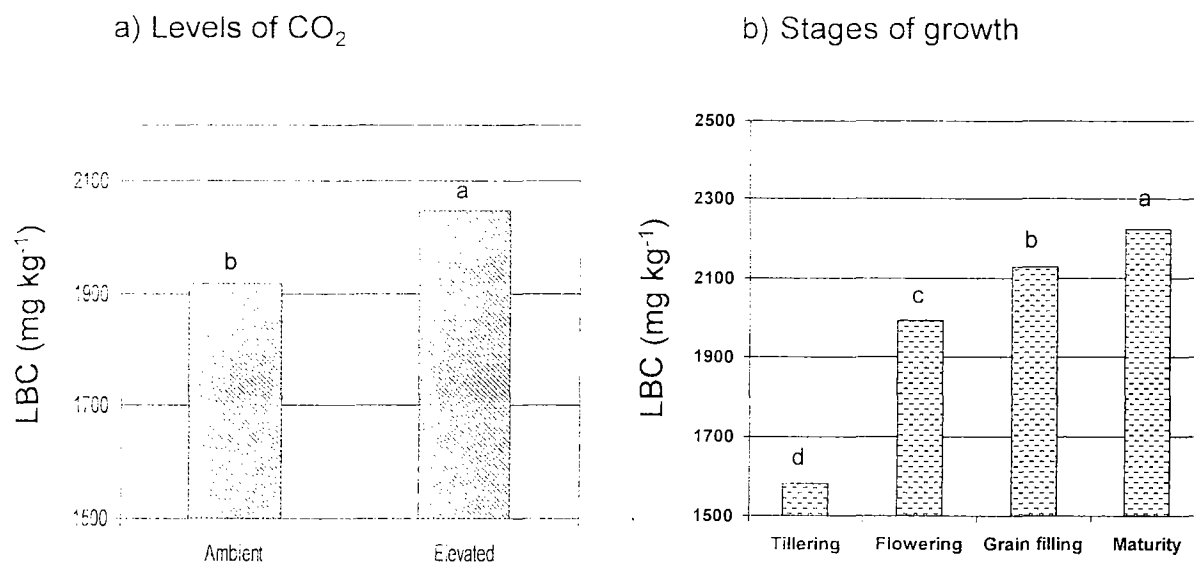


Table 20. Labile carbon contents (LBC, mg kg⁻¹) in rice rhizosphere at OTC as influenced by the interaction of levels of CO₂ and stages of crop growth

Growth stages	Levels of CO ₂	
	Ambient	Elevated
Tillering	1531 ^f	1630 ^e
Flowering	1912 ^d	2077 ^c
Grain filling	2054 ^c	2207 ^{ab}
Maturity	2173 ^b	2274 ^a

The differences between values with any common alphabet in figures or table are not statistically significant and *vice versa*

e) Total soil carbon

Total soil carbon (TSC) was measured by potassium dichromate digestion and this takes care of the resistant carbon compounds as well, besides the comparatively labile pools.

Values pertaining to total soil carbon content in rice rhizosphere soil as affected by elevation of CO₂ and stages of rice growth are presented in Table 21. Elevation of atmospheric CO₂ concentration did not affect the total soil carbon content. Regarding the influence of stages of crop growth, there was no significant change in TSC as the crop progressed from tillering to maturity. Interaction between these two factors was also not significant. No detectable change was observed with respect to the initial status also. Perhaps, no significant change can be expected in total soil carbon within a single crop season also.

B. Inorganic nitrogen pools

a) Ammoniacal nitrogen

Main effects of CO₂ levels and growth stages on ammoniacal nitrogen in rice rhizosphere soil are depicted in Figure 37. As a result of elevation of CO₂ concentration in crop atmosphere, a decrease in NH₄-N content by 16.66 per cent was observed in rice rhizosphere soil (Fig. 37a). Increased biomass production, root growth and translocation of biomass to underground portions under elevated CO₂ might have resulted in increased rate of uptake of NH₄-N by the crop, thus diminishing the pool size in soil.

With age of the crop, NH₄-N decreased significantly owing to uptake by the crop (Fig. 37b). All four stages of rice growth differed significantly and the values decreased with respect to previous stage.

Interaction between CO₂ levels and stages of growth had significant effect on NH₄-N content in crop rhizosphere, and the values are presented in Table 22. At tillering and maturity stage, the rice crop did not exhibit any influence of the elevation of atmospheric CO₂ concentration. At the other two stages, this pool of inorganic nitrogen was lower under elevated CO₂.

b) Nitrate nitrogen

Main effects of levels of CO₂ and growth stages on NO₃-N in rice rhizosphere soil are depicted in Figure 38. Elevation of atmospheric CO₂ did

Table 21. Total soil carbon contents (TSC, g kg⁻¹) in rice rhizosphere at OTC as influenced by elevated CO₂ at different stages of crop growth

Growth stages	Levels of CO ₂		Mean
	Ambient	Elevated	
Tillering	7.24 ^a	7.34 ^a	7.29 ^A
Flowering	7.33 ^a	7.58 ^a	7.46 ^A
Grain filling	7.47 ^a	7.66 ^a	7.56 ^A
Maturity	7.88 ^a	8.20 ^a	8.04 ^A
Mean	7.48 ^A	7.70 ^A	

The differences between values with any common alphabet in table are not statistically significant and *vice versa*

Values pertaining to the means related to a parameter (stages of crop growth or levels of CO₂) are to be compared among themselves only

Fig. 37. Ammoniacal nitrogen contents (mg kg^{-1}) in rice rhizosphere soil at OTC as influenced by:

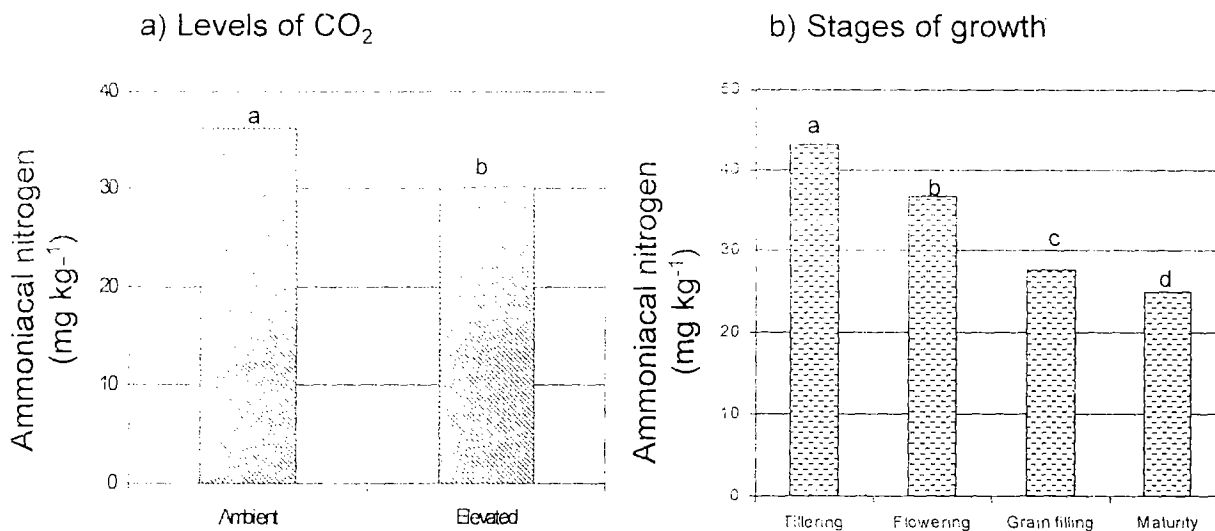


Table 22. Ammoniacal nitrogen contents (mg kg^{-1}) in rice rhizosphere soil at OTC as influenced by the interaction of levels of CO_2 and stages of crop growth

Growth stages	Levels of CO_2	
	Ambient	Elevated
Tillering	44.94 ^a	41.43 ^a
Flowering	41.63 ^a	31.89 ^b
Grain filling	32.14 ^b	23.23 ^c
Maturity	25.93 ^c	23.99 ^c

The differences between values with any common alphabet in figures or table are not statistically significant and *vice versa*

not affect this pool of inorganic nitrogen. Nevertheless, its value decreased slightly with age of the crop. Two-way interaction was also not significant (Table 23).

4.1.2 Wheat crop

4.1.2.1 Plant parameters

A. Plant biomass yield and partitioning

a) Stem dry weight

The stem dry weight of wheat as affected by elevation of CO₂ and stages of crop growth are presented in Figure 39. Exposure to higher atmospheric CO₂ concentration increased the stem dry weight by 21 per cent from 7.89 g pot⁻¹ under ambient CO₂ conditions (Fig. 39a). The stem dry weight was highest at grain filling stage, which was on par with the weight at anthesis, and later the value decreased towards maturity owing to the translocation of photosynthates to grain during this phase (Fig. 39b)

The interaction of levels of CO₂ and growth stages was significant and the values are presented in Table 24. Highest stem dry weight was obtained at grain filling stage under elevated CO₂, which was on par with the weight at anthesis stage at that CO₂ level. A decrease in stem dry weight by 9.98 per cent was observed under ambient condition from grain filling to maturity while, the decrease was by 20.56 per cent under elevated CO₂. This explains the positive role of higher CO₂ in photosynthesis and assimilation leading to increased harvest index. At all stages of crop growth except CRI, the values pertaining to stem dry matter were higher under elevated atmospheric CO₂ conditions. The CRI stage might be too early to establish the positive effect of elevation of atmospheric CO₂ concentration.

b) Leaf dry weight

The leaf dry weight of wheat crop as influenced by the main effects of levels of CO₂ and stages of crop growth are depicted in Figure 40. Leaf dry matter increased from 3.60 g pot⁻¹ under ambient CO₂ to 5.13 g pot⁻¹ under elevated CO₂ conditions (Fig. 40a). Thus elevation of atmospheric CO₂ produced an average increase of 42 per cent in leaf dry weight. The leaf dry weight continuously increased from CRI till grain filling stage and remained same thereafter at maturity (Fig. 40b).

Fig. 39. Stem dry matter (g pot^{-1}) of wheat grown in OTC as influenced by:

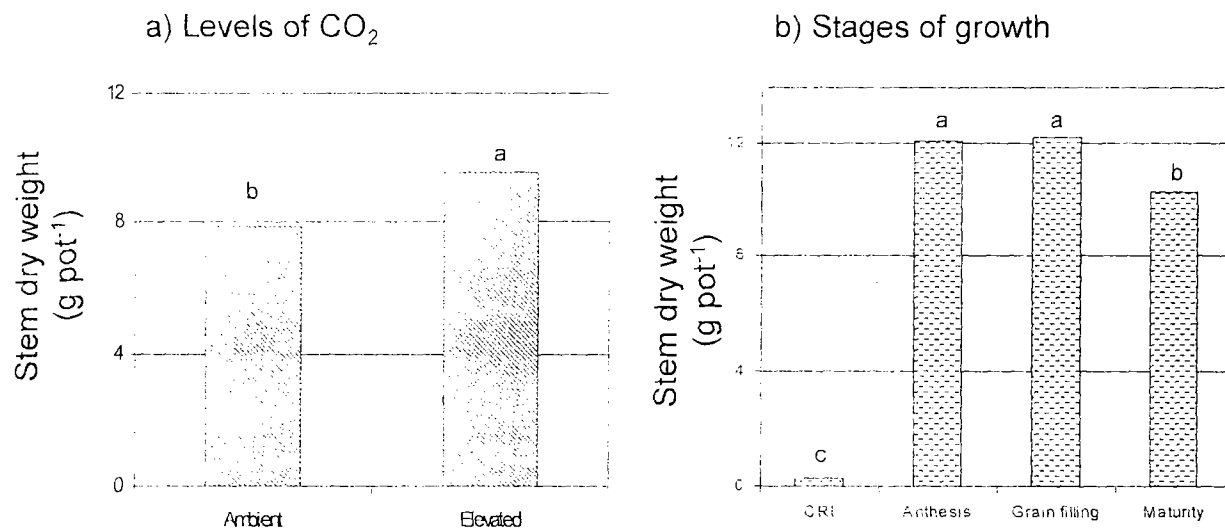


Table 24. Stem dry matter (g pot^{-1}) of wheat grown in OTC as influenced by the interaction of levels of CO₂ and stages of crop growth

Growth stages	Levels of CO ₂	
	Ambient	Elevated
CRI	0.265 ^d	0.290 ^d
Anthesis	11.11 ^b	13.08 ^a
Grain filling	10.62 ^{bc}	13.81 ^a
Maturity	9.56 ^c	10.97 ^b

The differences between values with any common alphabet in figures or table are not statistically significant and *vice versa*

CRI: Crown root initiation

Fig. 40. Leaf dry matter (g pot^{-1}) of wheat grown in OTC as influenced by:

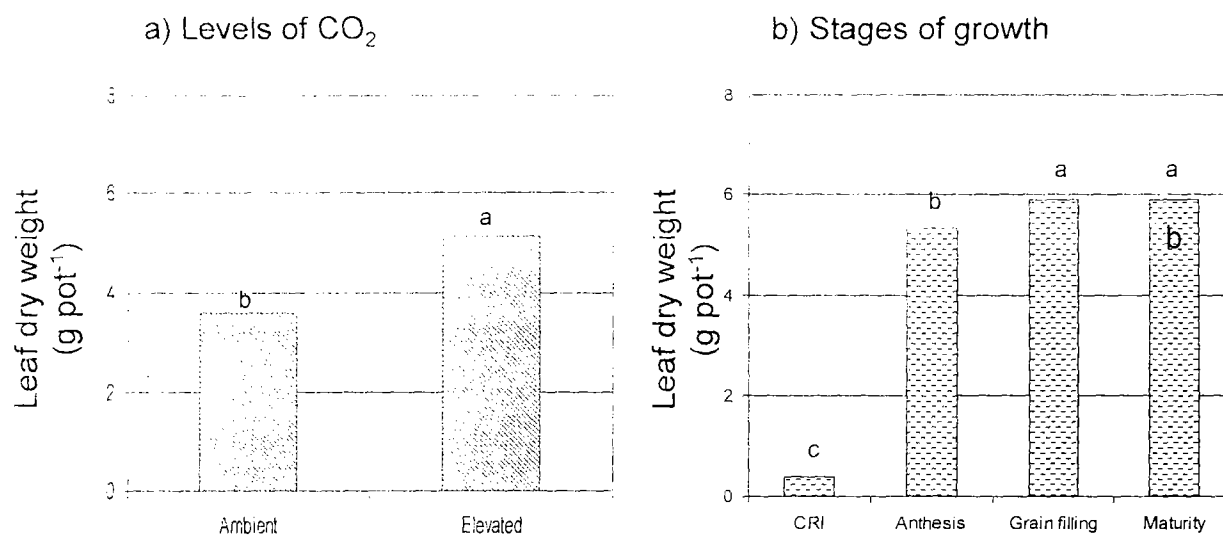


Table 25. Leaf dry matter (g pot^{-1}) of wheat grown in OTC as influenced by the interaction of levels of CO_2 and stages of crop growth

Growth stages	Levels of CO_2	
	Ambient	Elevated
CRI	0.354 ^c	0.411 ^c
Anthesis	4.191 ^b	6.436 ^a
Grain filling	4.935 ^b	6.829 ^a
Maturity	4.920 ^b	6.825 ^a

The differences between values with any common alphabet in figures or table are not statistically significant and *vice versa*

CRI: Crown root initiation

The interaction effect of levels of CO₂ and stages of crop growth on leaf dry weight of wheat was also significant and the values are presented in Table 25. Highest value of leaf dry weight was obtained at grain filling and maturity stages under elevated CO₂ condition (indicated by the Duncan value 'a' in superscript). There was no significant difference between two CO₂ levels with respect to the values of leaf dry weight at CRI stage. At all other stages, elevated CO₂ treatments recorded higher values over the ambient ones.

c) Root dry weight

Values pertaining to root dry matter as affected by levels of CO₂ and stages of crop growth are presented in Figure 41. Treatments belonging to elevated CO₂ produced an average root dry weight of 2.49 g pot⁻¹ while those belonging to ambient CO₂ produced 1.46 g pot⁻¹, thus amounting to an increase of 70.54 per cent due to elevation of CO₂ (Fig. 41a). Root dry weight increased from CRI to anthesis stage, and subsequently decreased towards maturity (Fig. 41b). This could be due to the probable decay in root mass that subsequently must have been turned over in wheat rhizosphere.

Interaction effect was significant and the values are presented in Table 26. Highest root dry weight was recorded at anthesis stage under elevated CO₂ condition. The values of root dry weight under elevated CO₂ at anthesis and grain filling stages were higher than the corresponding values under ambient CO₂ conditions, while CRI stage was found to be too early to express the positive effect of elevation of atmospheric CO₂ concentration. Again at maturity, the values of root dry weight were at par in both the CO₂ levels. This signifies increased turnover of root dry matter in soil under elevated atmospheric CO₂.

d) Grain weight

The weight of wheat grains as affected by elevation of atmospheric CO₂ is given in Figure 42. Elevation of CO₂ in atmosphere resulted in an increase in grain yield by 35.39 per cent from a value of 10.34 g pot⁻¹ under ambient CO₂ to 14.00 g pot⁻¹ under elevated CO₂ condition.

e) Total Biomass and its partitioning

Total dry matter yield of wheat as functions of levels of CO₂ and stages of crop growth are presented in Figure 43. Elevation of atmospheric CO₂

Fig. 41. Root dry matter (g pot^{-1}) of wheat grown in OTC as influenced by:

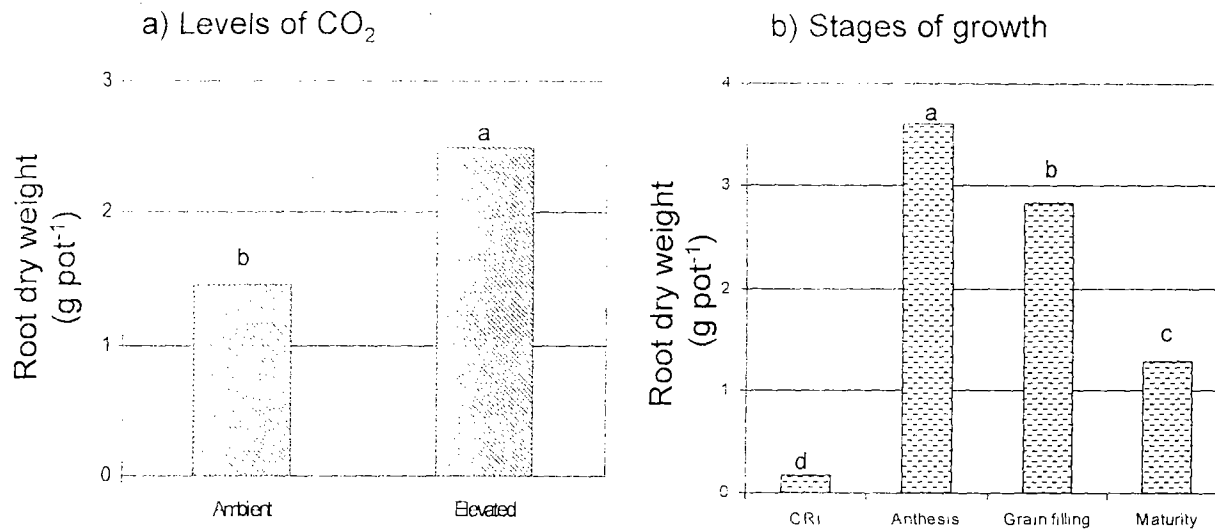


Table 26. Root dry matter (g pot^{-1}) of wheat grown in OTC as influenced by the interaction of levels of CO₂ and stages of crop growth

Growth stages	Levels of CO ₂	
	Ambient	Elevated
CRI	0.141 ^f	0.201 ^f
Anthesis	2.730 ^c	4.473 ^a
Grain filling	1.873 ^d	3.773 ^b
Maturity	1.075 ^e	1.510 ^{de}

The differences between values with any common alphabet in figures or table are not statistically significant and *vice versa*

CRI: Crown root initiation

Fig. 42. Grain weight (g pot⁻¹) of wheat grown in OTC as influenced by the elevation of atmospheric CO₂ concentration

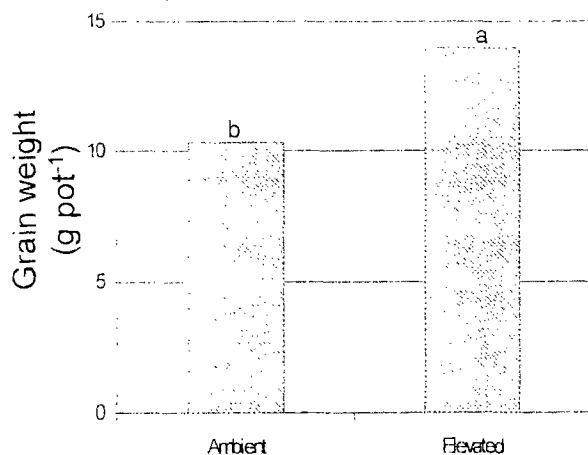
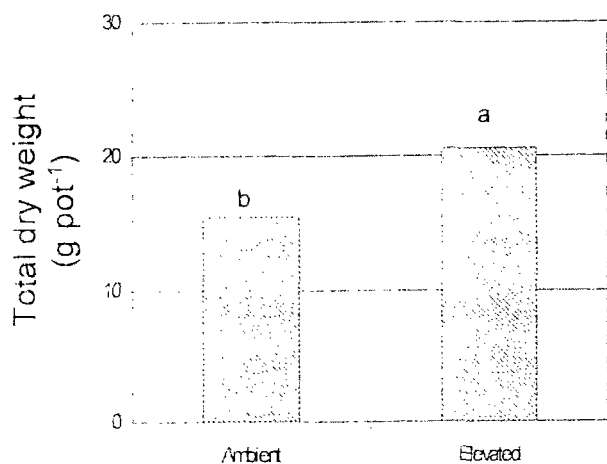
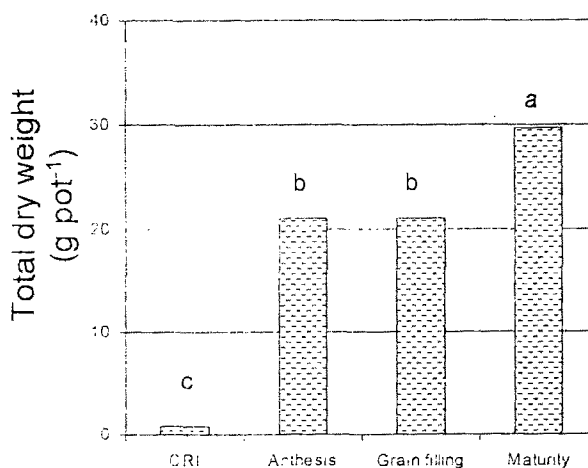


Fig. 43. Total dry matter yield (g pot⁻¹) of wheat grown in OTC as influenced by:

a) Levels of CO₂



b) Stages of growth



The differences between values with any common alphabet in figures are not statistically significant and *vice versa*

CRI: Crown root initiation

concentration increased the total biomass yield of wheat from 15.53 g pot⁻¹ under ambient CO₂ to 20.6 g pot⁻¹ amounting to a 32.98 per cent gain (Fig. 43a).

Regarding stages of wheat growth, total biomass yield increased significantly as the crop progressed from CRI to maturity (Fig. 43b). However, anthesis and grain filling stages did not differ significantly with respect to total biomass yield. Even though there was decrease in root weight and stem dry weight at maturity, the total biomass increased due to the contribution from grain weight. The rate of increase in biomass yield was maximum between CRI and flowering stages as this phase represents the active period of vegetative growth. The rate of increase was smaller when crop progressed from flowering to maturity due to the decay of roots and translocation and assimilation of photosynthates during reproductive phase.

Interaction between stages of crop growth and levels of CO₂ was also significant and the values are recorded in Table 27. At all stages of wheat growth the total biomass yield was higher when the crop was grown under elevated CO₂ concentration. Highest biomass yield was produced by wheat at maturity under elevated CO₂. The total biomass yield of the crop at flowering under elevated CO₂ concentration was on par with that at grain filling stage under elevated CO₂, and with the yield at maturity under ambient condition. The CRI stage was too early in the crop cycle to detect any positive effect of the increase in atmospheric CO₂ concentration.

Elevation of atmospheric CO₂ significantly affected the biomass distribution pattern in different plant parts in wheat. The distribution patterns at different stages of wheat growth under ambient and elevated atmospheric CO₂ conditions are depicted in Figure 44. The per cent biomass allocation to belowground portion decreased with age of the crop under both ambient and elevated CO₂ concentrations. This decrease can be ascribed to the increased rate of stem and leaf growth in the initial vegetative phase and the degradation of roots and photosynthetic translocation to grain in the reproductive phase. The decrease was maximum between anthesis and maturity as this period represented the period of intense decay of root dry matter. Irrespective of the levels of CO₂, a decrease in preferential biomass

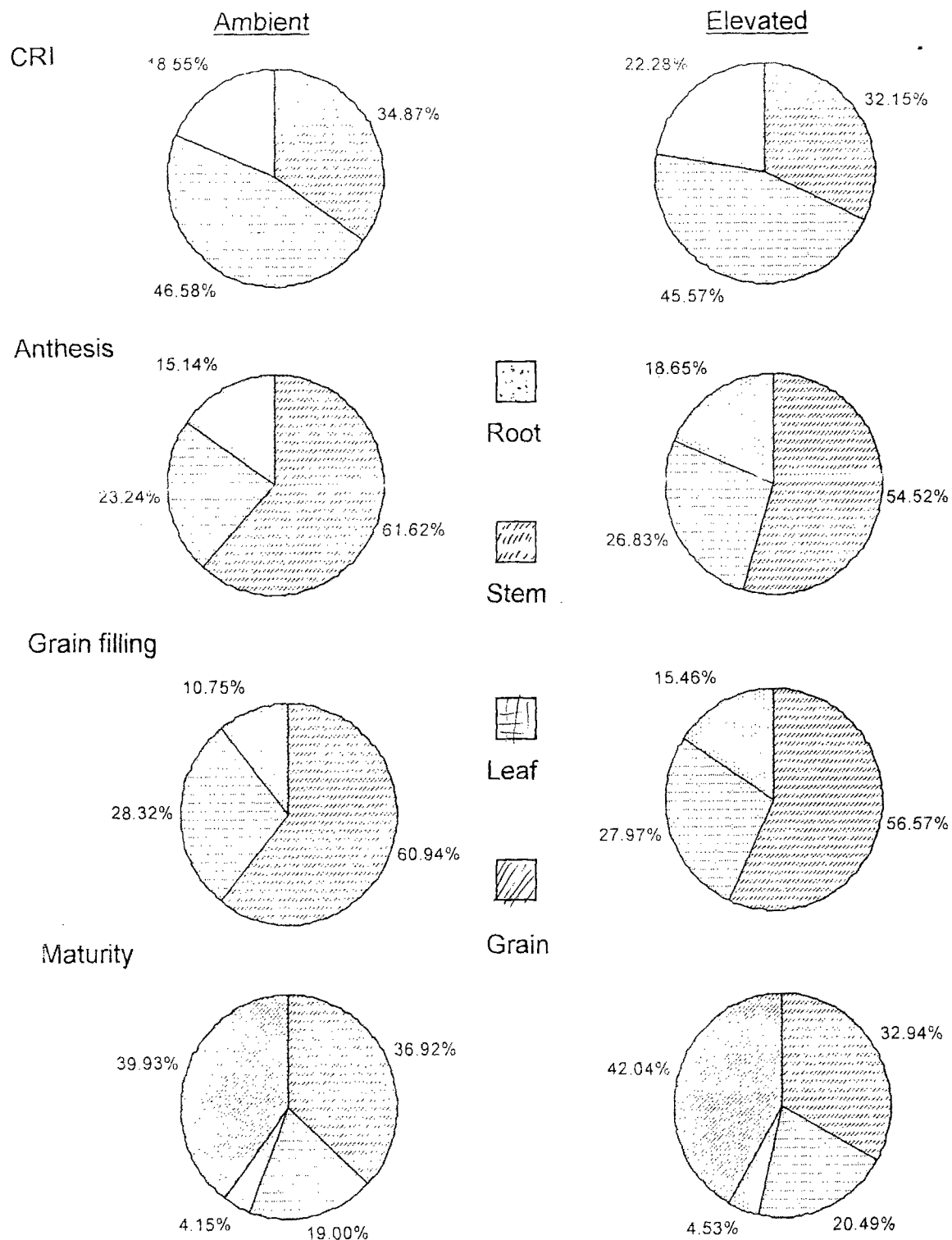
Table 27. Total dry matter yield (g pot⁻¹) of wheat grown in OTC as influenced by the interaction of levels of CO₂ and stages of crop growth

Growth stages	Levels of CO ₂	
	Ambient	Elevated
CRI	0.760 ^e	0.898 ^e
Anthesis	18.03 ^d	23.99 ^c
Grain filling	17.43 ^d	24.41 ^{bc}
Maturity	25.90 ^b	33.31 ^a

The differences between values with any common alphabet in table are not statistically significant and *vice versa*

CRI: Crown root initiation

Fig. 44. Biomass partitioning to different plant parts at various stages of wheat grown in OTC as affected by elevation of atmospheric CO₂ concentration



CRI: Crown root initiation

portioning to leaves was also observed as the crop aged and this can be ascribed to the preferential partitioning to other parts like stem, root and grains.

The partitioning towards stem increased as the crop progressed from CRI to anthesis, remained as such till grain filling and later decreased again towards maturity due to the translocation of photosynthates to grain.

The two levels of atmospheric CO₂ exhibited quite different biomass patterns of distribution at the four physiological stages of wheat. At all the four stages of growth the per cent biomass allocation belowground to root was higher under elevated CO₂. In general the portioning towards both stem and leaves were lower under elevated CO₂ concentration as a result of the increased apportioning towards roots. However at anthesis and maturity stages the contribution of leaf too was slightly higher under elevated CO₂. The per cent dry matter accumulation in grain was slightly higher under elevated CO₂, which suggested the positive role of elevated CO₂ on harvest index.

f) Fresh root weight

Values pertaining to fresh root weight as functions of levels of CO₂ and stages of crop growth are presented in Figure 45. Treatments with elevated CO₂ had an average fresh root weight of 14.10 g pot⁻¹ while those belonging to ambient CO₂ produced 8.15 g pot⁻¹, thus amounting to an increase by 73.01 per cent (Fig. 45a). As observed in case of root dry weight, fresh root weight increased from CRI to anthesis stage, and subsequently decreased towards maturity (Fig. 45b).

Interaction effect was significant and the values are presented in Table 28. Highest amount of roots in terms of fresh weight was produced by wheat at anthesis stage under elevated CO₂ condition. The values of fresh root weight under elevated CO₂ at different stages of wheat growth were significantly higher than the corresponding values under ambient CO₂ conditions with an exception of CRI stage.

g) Root volume

Values pertaining to root volume as affected by levels of CO₂ and stages of crop growth are presented in Figure 46. Treatments belonging to ambient CO₂ produced an average volume of 8.70 ml pot⁻¹ while those

Fig. 45. Fresh root weight (g pot⁻¹) of wheat grown in OTC as influenced by:

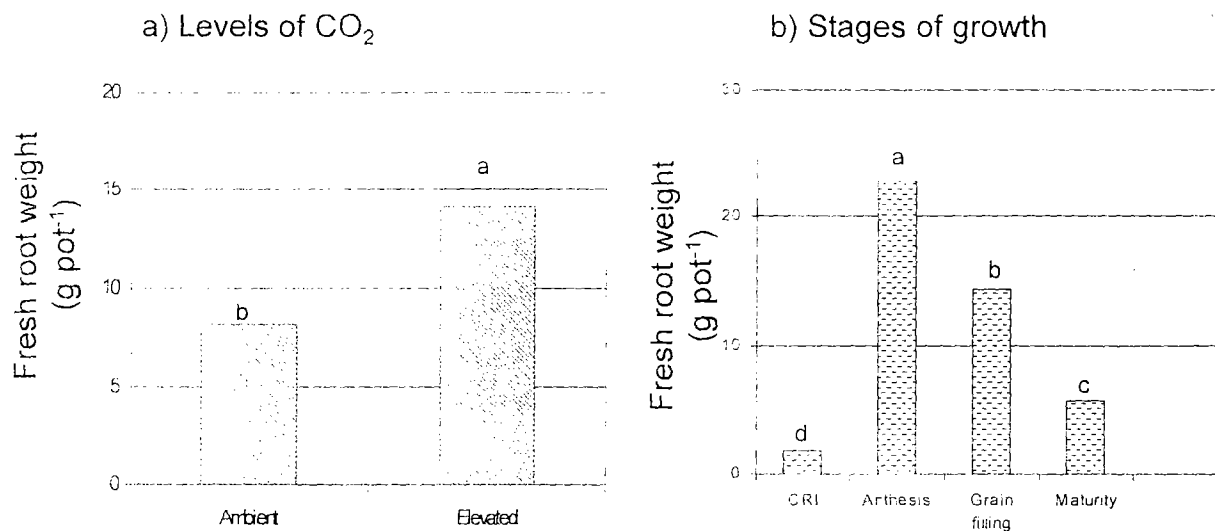


Table 28. Fresh root weight (g pot⁻¹) of wheat grown in OTC as influenced by the interaction of levels of CO₂ and stages of crop growth

Growth stages	Levels of CO ₂	
	Ambient	Elevated
CRI	1.375 ^g	2.292 ^g
Anthesis	17.61 ^c	27.82 ^a
Grain filling	9.234 ^d	19.34 ^b
Maturity	4.400 ^f	6.955 ^e

The differences between values with any common alphabet in figures or table are not statistically significant and *vice versa*

CRI: Crown root initiation

belonging to elevated CO₂ had 15.41 ml pot⁻¹ volume, thus amounting to an increase of 77.13 per cent (Fig. 46a).

Volume of roots increased from CRI to anthesis stage, and subsequently decreased towards maturity (Fig. 46b). A similar trend was observed in fresh as well as dry weights of wheat roots (Fig 41 and 45b).

Interaction effect was significant and the values are presented in Table 29. Highest root volume in wheat was observed at anthesis stage under elevated CO₂ condition. The values of root volume under elevated CO₂ at different stages of wheat growth were higher than the corresponding values under ambient CO₂ conditions except CRI stage. It is interesting to note that the decrease in root volume under ambient CO₂ concentration was maximum between anthesis and grain filling stages, while that under elevated CO₂ occurred between grain filling and maturity. This was observed in case of root weights also.

B. Carbon and nitrogen uptake and partitioning

a) Content and uptake of carbon by stem

The stem carbon contents as affected by levels of CO₂ and stages of crop growth are presented in Figure 47. Exposure to enhanced CO₂ concentration did not have any significant effect on carbon content in stem (Fig. 47a).

The values of carbon uptake by stem in wheat crop as affected by CO₂ and stages of crop growth are presented in Figure 48. As a consequence of the increase in biomass yield, average carbon uptake by stem dry matter increased by 22.18 per cent from 2.75 g pot⁻¹ in ambient to 3.36 g pot⁻¹ in elevated CO₂ condition (Fig. 48a).

Stages of wheat also did not have any significant effect on carbon concentration in stem except an increase towards maturity, thus making the main effect significant (Fig. 47b). The uptake of carbon by wheat stem showed an increasing trend till grain filling followed by decrease at maturity owing to the plant biomass yield pattern across the stages (Fig. 48b). Highest rate of increase in C uptake was observed in the active vegetative phase of wheat growth *ie.*, between CRI and anthesis stages.

Fig. 47. Stem carbon concentration (per cent) in wheat grown in OTC as influenced by:

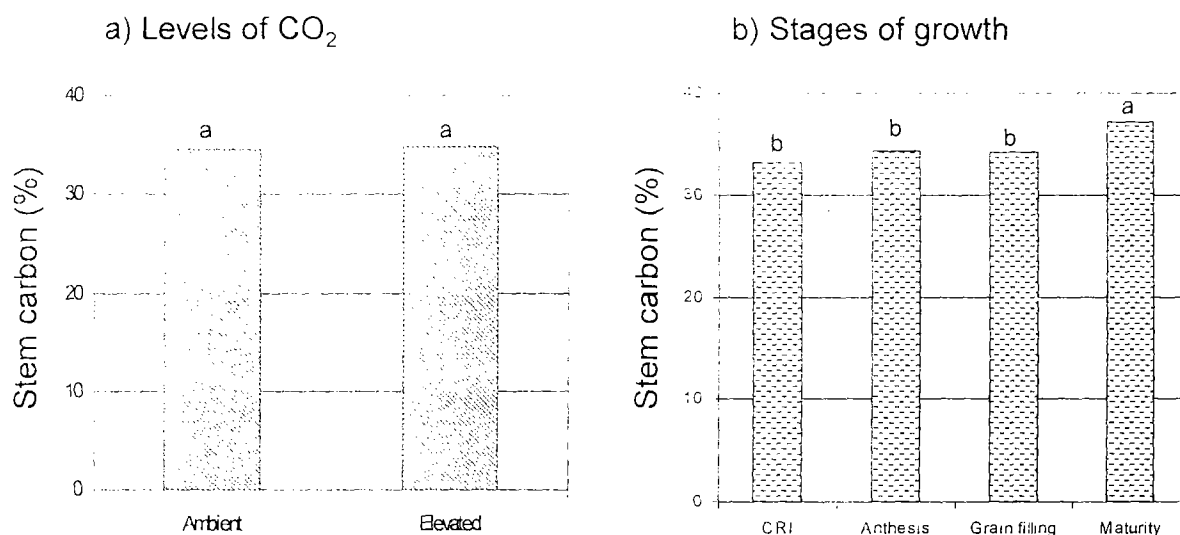


Table 30. Carbon concentration (per cent) in the stem of wheat grown in OTC as influenced by the interaction of levels of CO₂ and stages of crop growth

Growth stages	Levels of CO ₂	
	Ambient	Elevated
CRI	33.44 ^{bc}	32.85 ^c
Anthesis	34.57 ^{bc}	33.98 ^{bc}
Grain filling	34.85 ^{bc}	33.48 ^{bc}
Maturity	35.37 ^b	38.91 ^a

The differences between values with any common alphabet in figures or table are not statistically significant and *vice versa*

CRI: Crown root initiation

Fig. 48. Carbon uptake (mg pot^{-1}) by stem dry matter of wheat grown in OTC as influenced by:

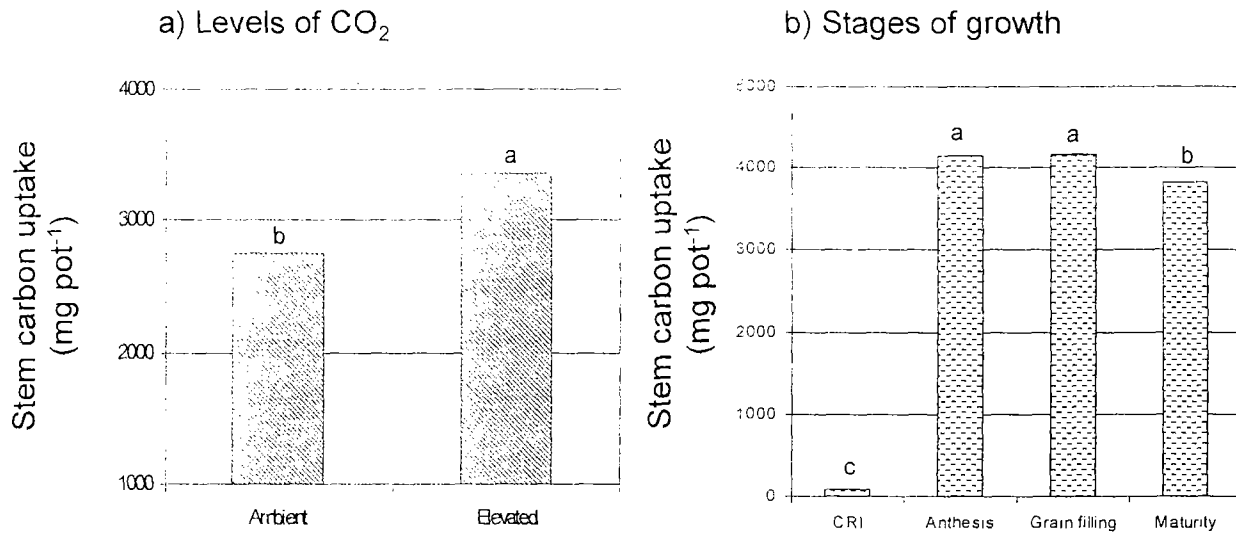


Table 31. Carbon uptake (mg pot^{-1}) by stem dry matter of wheat grown in OTC as influenced by the interaction of levels of CO_2 and stages of crop growth

Growth stages	Levels of CO_2	
	Ambient	Elevated
CRI	88.50 ^d	93.99 ^d
Anthesis	3835 ^b	4443 ^a
Grain filling	3700 ^{bc}	4615 ^a
Maturity	3377 ^c	4269 ^a

The differences between values with any common alphabet in figures or table are not statistically significant and *vice versa*

CRI: Crown root initiation

Interaction between levels of CO₂ and growth stages influenced the carbon content in stem with highest carbon concentration associated with the maturity stage of crop under elevated CO₂ (Table 30). This was reflected further in the uptake of carbon by stem (Table 31). Though the dry weight of stem showed a decreasing trend from grain filling to maturity, values of uptake of carbon did not follow the same pattern and were at par both in case of elevated and ambient CO₂ conditions due to concentration effect of C on wheat stem.

b) Content and uptake of carbon by leaves

The average values of C concentration in leaf as individually influenced by levels of CO₂ and stages of wheat growth are presented in Figure 49.

Elevation of CO₂ concentration in atmosphere did not have any significant effect on C content in leaves of wheat either (Fig. 49a). The values of carbon uptake by leaves as affected by CO₂ and stages of crop growth are presented in Figure 50. It is evident from fig 50a that C uptake increased by 42.57 per cent as a result of higher CO₂ concentration in atmosphere. This can be clearly ascribed to the increased leaf dry matter yield under elevated CO₂.

The C content in leaf remained unchanged with age of the crop (Fig. 49b). However leaf C uptake increased sharply as the crop progressed from CRI to anthesis, and later remained same towards maturity (Fig. 50b). A similar trend was observed with respect to leaf dry matter yield (Fig. 40b). Though a significant increase in leaf dry weight was observed between anthesis and grain filling stages, the increase in C uptake value between these stages was statistically insignificant.

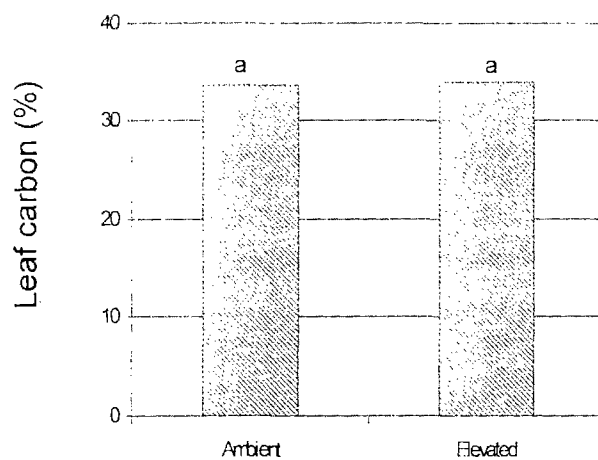
The interaction between levels of CO₂ and growth stages was significant only in case of leaf C uptake and values are presented in Table 32. Carbon uptake by leaves was highest towards the end of vegetative growth under elevated CO₂ and thereafter value remained at par till maturity.

c) Content and uptake of carbon by roots

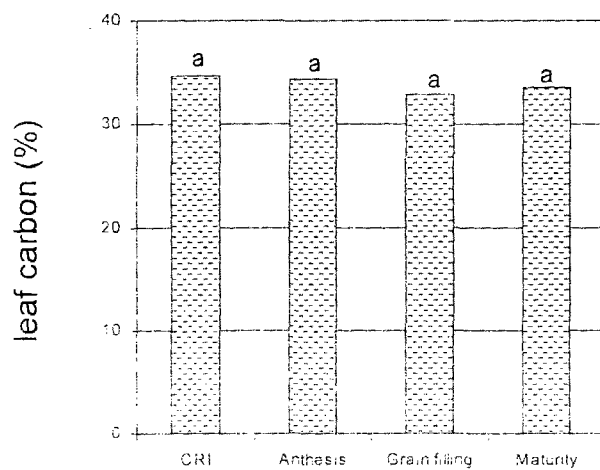
The average carbon concentration in roots as affected by elevation of CO₂ in atmosphere and the stages of crop growth are depicted in Figure 51.

Fig. 49. Leaf carbon concentration (per cent) in wheat grown in OTC as influenced by:

a) Levels of CO₂



b) Stages of growth



The differences between values with any common alphabet in figures are not statistically significant and vice versa

CRI: Crown root initiation

Fig. 50. Carbon uptake (mg pot^{-1}) by leaf dry matter of wheat grown in OTC as influenced by:

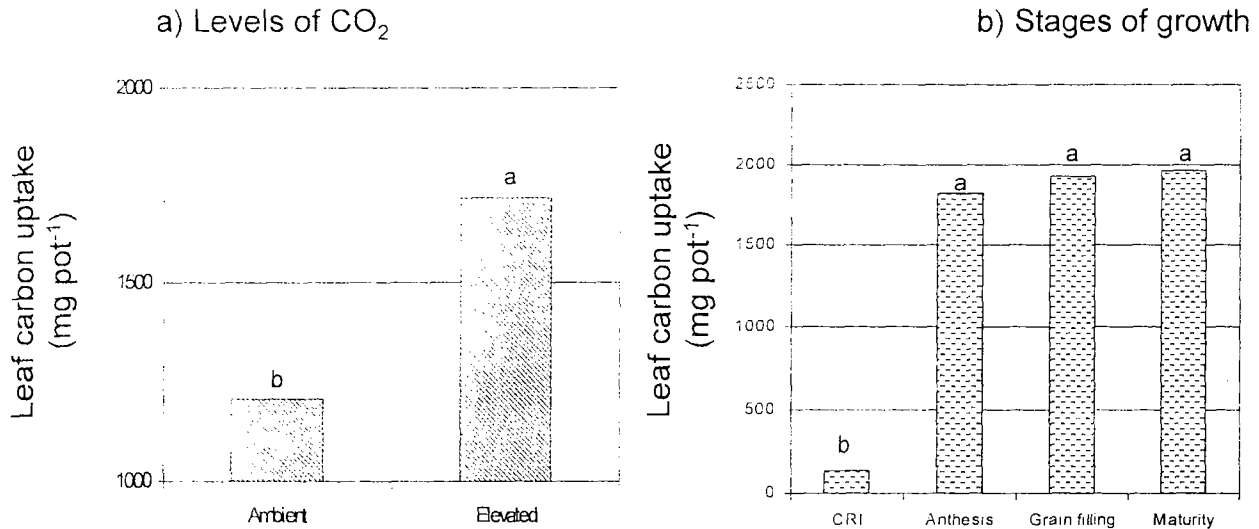


Table 32. Carbon uptake (mg pot^{-1}) by leaf dry matter of wheat grown in OTC as influenced by the interaction of levels of CO₂ and stages of crop growth

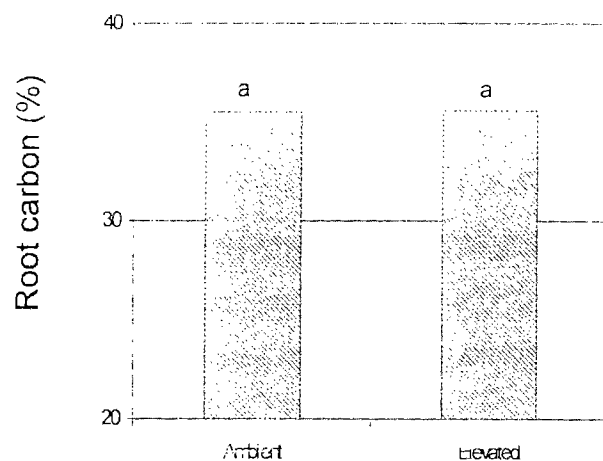
Growth stages	Levels of CO ₂	
	Ambient	Elevated
CRI	120.9 ^c	144.0 ^c
Anthesis	1425 ^b	2215 ^a
Grain filling	1612 ^b	2249 ^a
Maturity	1663 ^b	2265 ^a

The differences between values with any common alphabet in figures or table are not statistically significant and *vice versa*

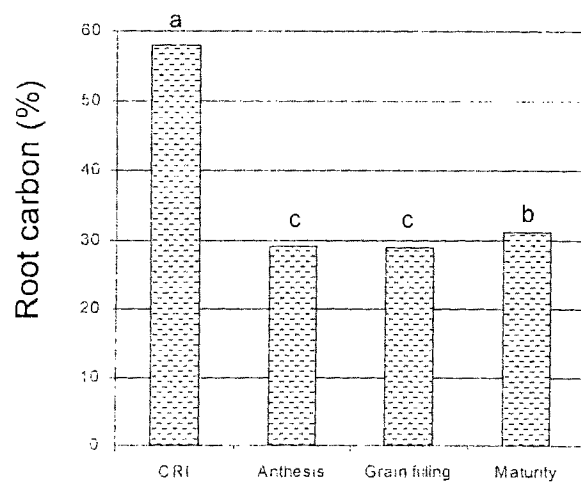
CRI: Crown root initiation

Fig. 51. Root carbon concentration (per cent) in wheat grown in OTC as influenced by:

a) Levels of CO₂



b) Stages of growth



The differences between values with any common alphabet in figures are not statistically significant and *vice versa*

CRI: Crown root initiation

Like stem and leaf, elevation of atmospheric CO₂ did not produce any significant influence on the C content in wheat roots (Fig. 51a). Regarding stages, the C concentration was highest at CRI, thereafter decreased and got stabilized till grain filling, and then increased slightly towards maturity (Fig. 51b).

The values of carbon uptake by roots as affected by CO₂ and stages of crop growth are presented in Figure 52. Given the fact that average root dry matter was higher, elevation of atmospheric CO₂ caused an additional consumption of 305.5 mg pot⁻¹ over 435.1 mg pot⁻¹ under ambient CO₂, thus amounting to a 70.21 per cent increase (Fig. 52a).

Regarding the stages of wheat growth, root C uptake data followed the same trend as that of root dry matter (Fig. 41b) with highest value observed at anthesis stage in spite of the sharp decline in C concentration from CRI stage onwards (Fig. 52b).

The interaction had significant effect on root C uptake and the values are presented in Table 33. Root C uptake by wheat was observed to be highest at anthesis under elevated CO₂. Excepting CRI, the other three stages experienced significant gain in C uptake by root under elevated atmospheric CO₂ when compared with the corresponding values under ambient CO₂.

d) Content and uptake of carbon by grains

Carbon content and its uptake by rice grains as a function of levels of CO₂ are given in Figures 53 and 54, respectively. Eventhough elevation of atmospheric CO₂ concentration did not affect the C composition of rice grains; the uptake was augmented owing to the increase in dry weight.

e) Total carbon uptake and its partitioning

Total carbon uptake by wheat as a function of levels of CO₂ and stages of growth are given in Figure 55. The average total carbon uptake by wheat was increased by 33.25 per cent in response to the elevation of atmospheric CO₂ concentration (Fig. 55a). With advancement towards maturity, an increase in plant carbon uptake was observed (Fig. 55b). It is very evident from the figure that the increase was sharper between CRI and anthesis stages and this represents the most active vegetative phase of crop growth wherein faster rate of accumulation of photosynthates was expected. Between

Fig. 52. Carbon uptake (mg pot^{-1}) by roots of wheat grown in OTC as influenced by:

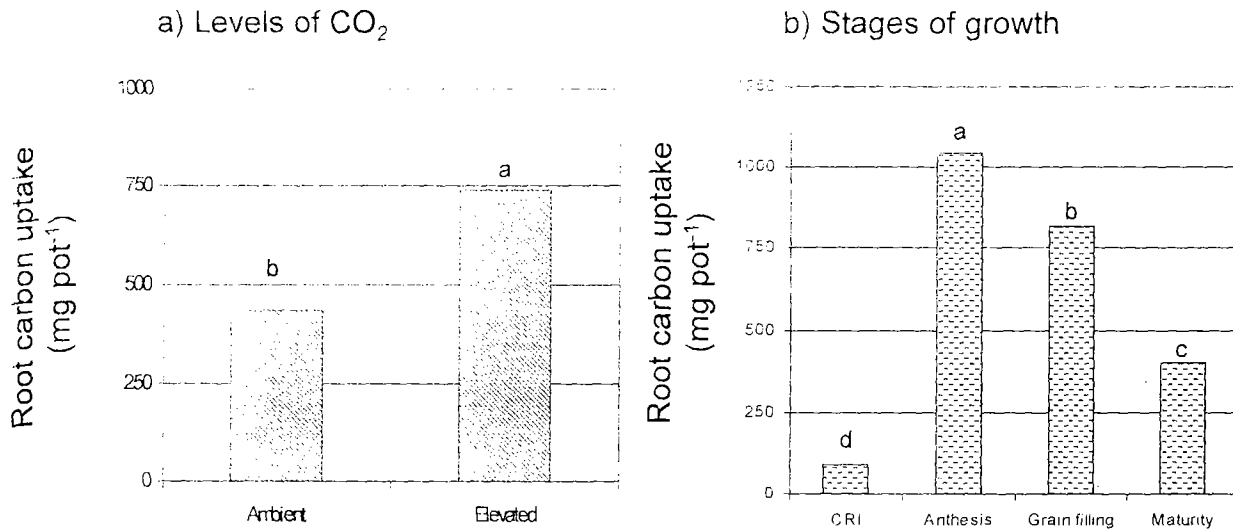


Table 33. Carbon uptake (mg pot^{-1}) by roots of wheat grown in OTC as influenced by the interaction of levels of CO_2 and stages of crop growth

Growth stages	Levels of CO_2	
	Ambient	Elevated
CRI	74.69 ^f	106.6 ^f
Anthesis	793.0 ^c	1293 ^a
Grain filling	538.8 ^d	1093 ^b
Maturity	333.8 ^e	470.2 ^d

The differences between values with any common alphabet in figures or table are not statistically significant and *vice versa*

CRI: Crown root initiation

Fig. 53. Carbon concentration (per cent) in the grains of wheat grown in OTC as influenced by the elevation of atmospheric CO₂ concentration

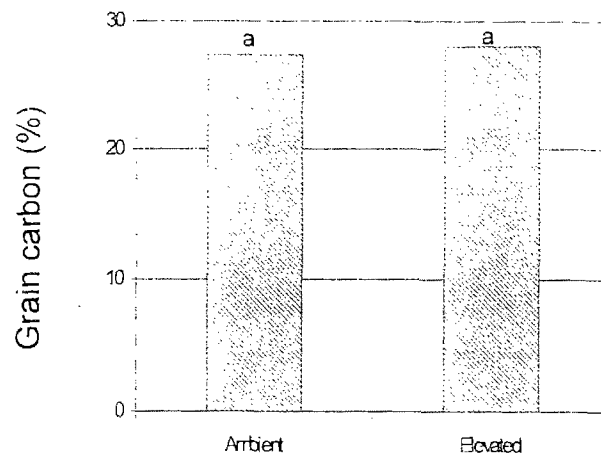
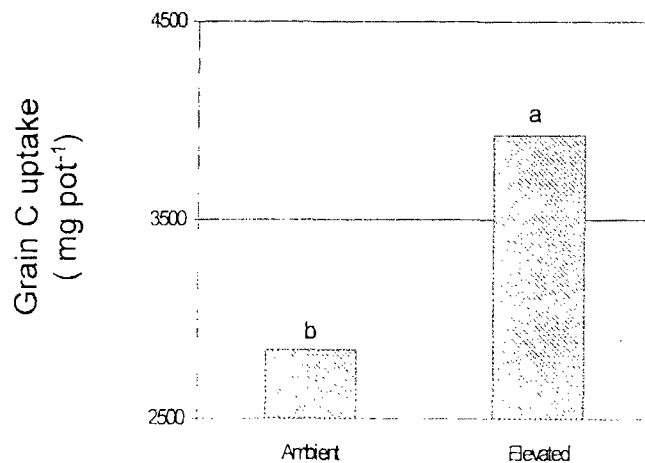


Fig. 54. Carbon uptake by the grains of wheat crop at OTC as influenced by the elevation of atmospheric CO₂ concentration



The differences between values with any common alphabet in figures are not statistically significant and *vice versa*

CRI: Crown root initiation

Fig. 55. Total carbon uptake (mg pot^{-1}) by wheat grown in OTC as influenced by:

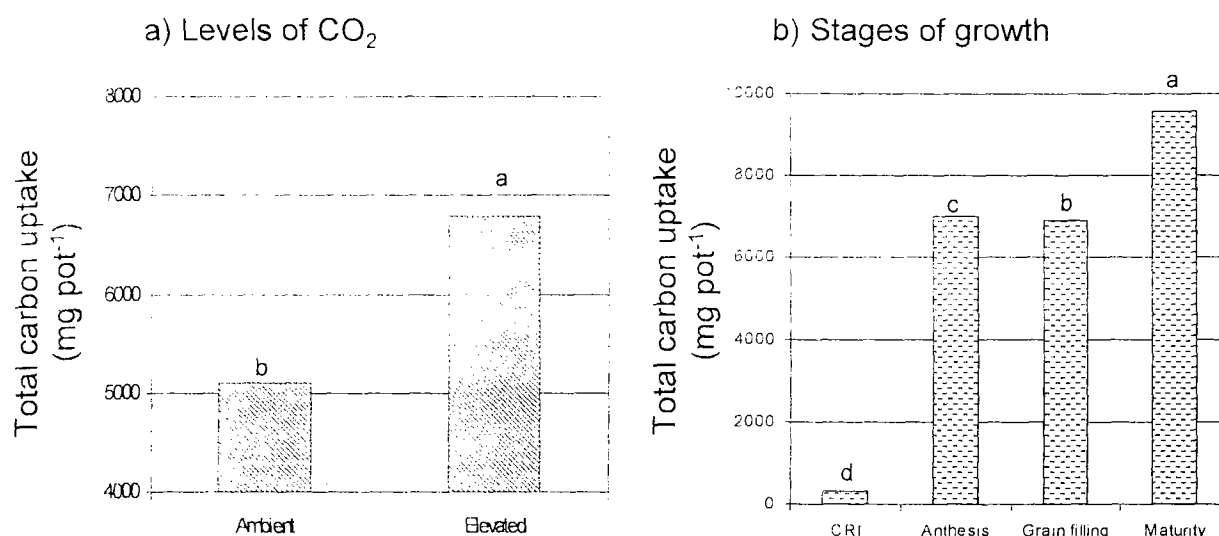


Table 34. Total carbon uptake (mg pot^{-1}) by wheat grown in OTC as influenced by the interaction of levels of CO₂ and stages of crop growth

Growth stages	Levels of CO ₂	
	Ambient	Elevated
CRI	284.1 ^d	344.6 ^d
Anthesis	6053 ^c	7951 ^b
Grain filling	5851 ^c	7956 ^b
Maturity	8211 ^b	10929 ^a

The differences between values with any common alphabet in figures or table are not statistically significant and *vice versa*

CRI: Crown root initiation

flowering and grain filling stages the value did not show any significant change while the increased accumulation of carbon in grain augmented the total carbon accumulation at maturity.

The interaction between levels of CO₂ and crop growth stages was significant and the values are presented in Table 34. Carbon uptake increased as the crop approached maturity when grown under ambient as well as elevated CO₂. But the positive effect of elevation of atmospheric CO₂ concentration was visible only in the later phase of crop growth (anthesis and beyond). The carbon assimilation at CRI stage was too low to show any positive influence of the increase in atmospheric CO₂.

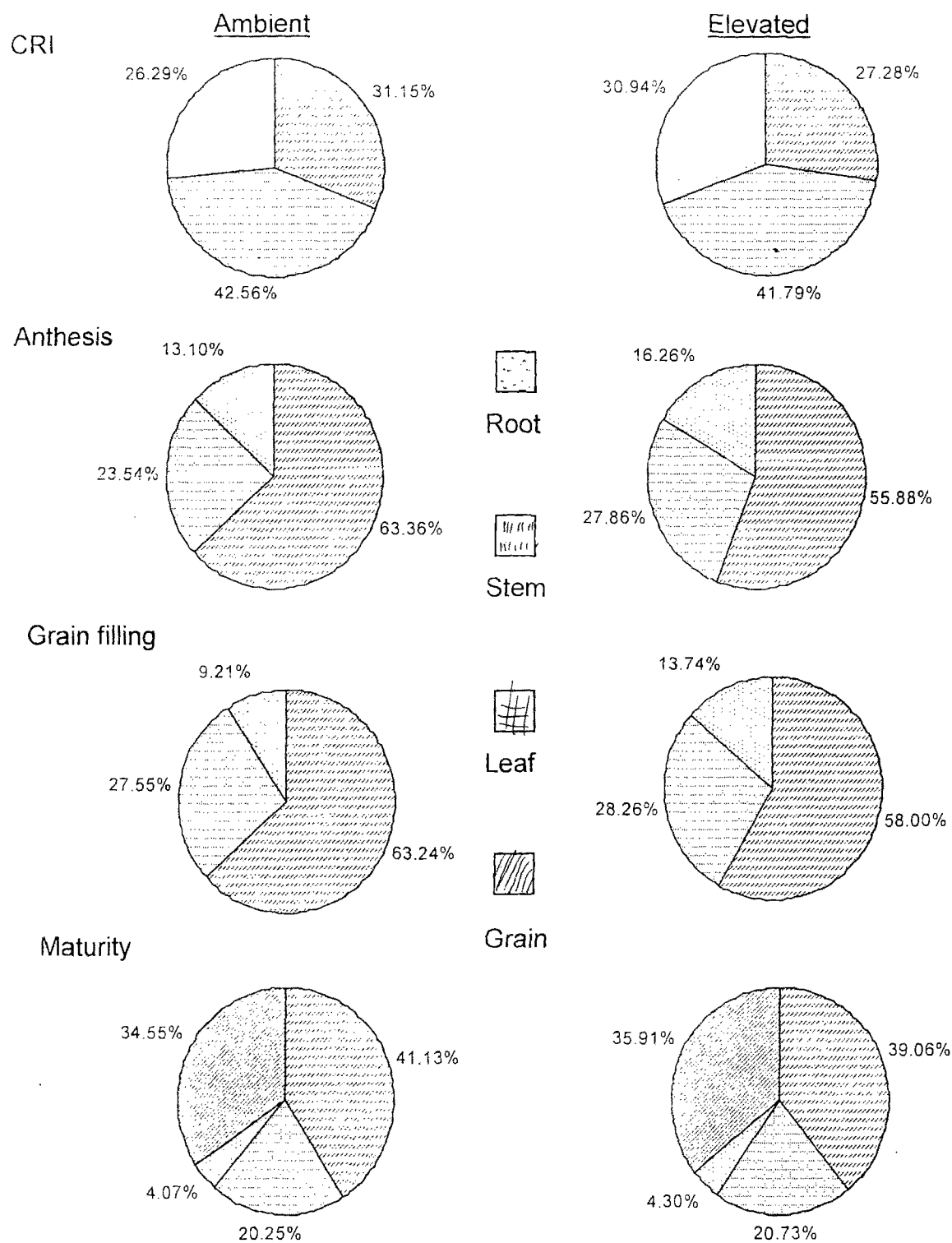
Carbon partitioning in different plant parts at four physiological stages of wheat under ambient as well as elevated CO₂ conditions are presented in Figure 56. At all crop growth stages, exposure to higher CO₂ increased the relative partitioning of carbon to roots. It may be recalled that this trend was observed in case of biomass partitioning also (Fig. 44). As a result, per cent carbon allocated below ground increased from 26.29 to 30.94 per cent at CRI stage of wheat growth, while the corresponding increases at anthesis, grain filling and maturity were from 13.10 to 16.26, 9.21 to 13.74 and 4.07 to 4.30, respectively. At all stages of wheat growth the preferential portioning of photosynthates to stem was higher under ambient CO₂, while the apportioning towards leaf dry matter was generally higher under elevated CO₂ with an exception at CRI stage. The per cent accretion of C in grains increased from 34.55 to 35.91 in response to the elevation of CO₂ concentration in atmosphere.

With age of the crop, carbon partitioning to roots decreased continuously, irrespective of the levels of CO₂. The C partitioning data exhibited exactly the same trends as those of biomass partitioning with regard to the changes with age of the crop.

f) Nitrogen content and C:N ratio of stem dry matter

The values pertaining to per cent nitrogen content and C:N ratio of the stem dry matter of wheat as affected by levels of CO₂ and stages of crop growth are presented in Figures 57 and 58, respectively. Though elevation of atmospheric CO₂ concentration did not affect the N concentration (Fig. 57a),

Fig. 56. Carbon partitioning to different plant parts at various stages of wheat grown in OTC as affected by elevation of atmospheric CO₂ concentration



CRI: Crown root initiation

Fig. 57. Nitrogen concentration (per cent) in the stem dry matter of wheat grown in OTC as influenced by:

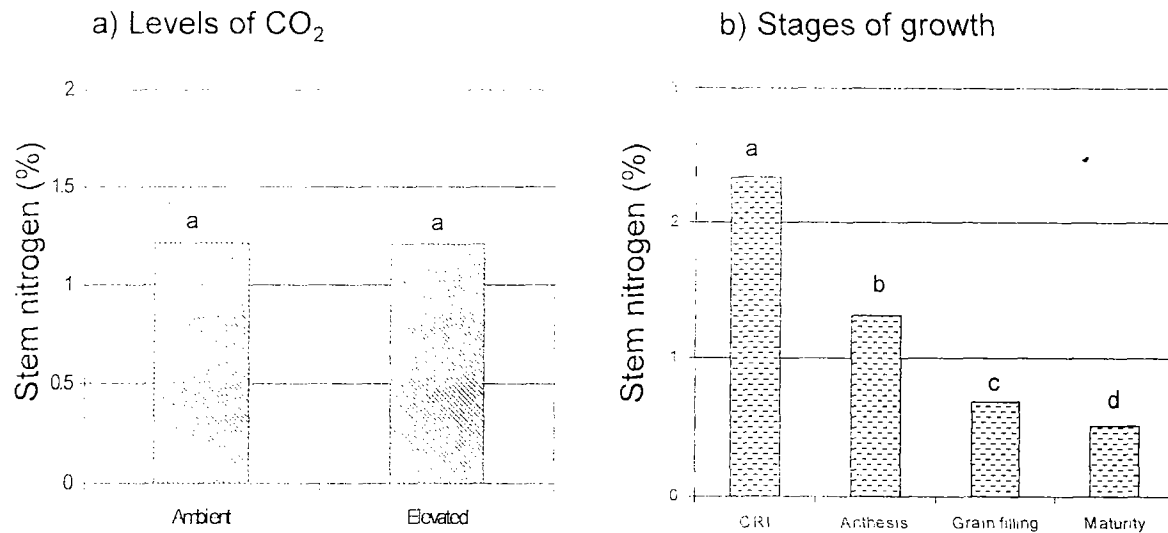
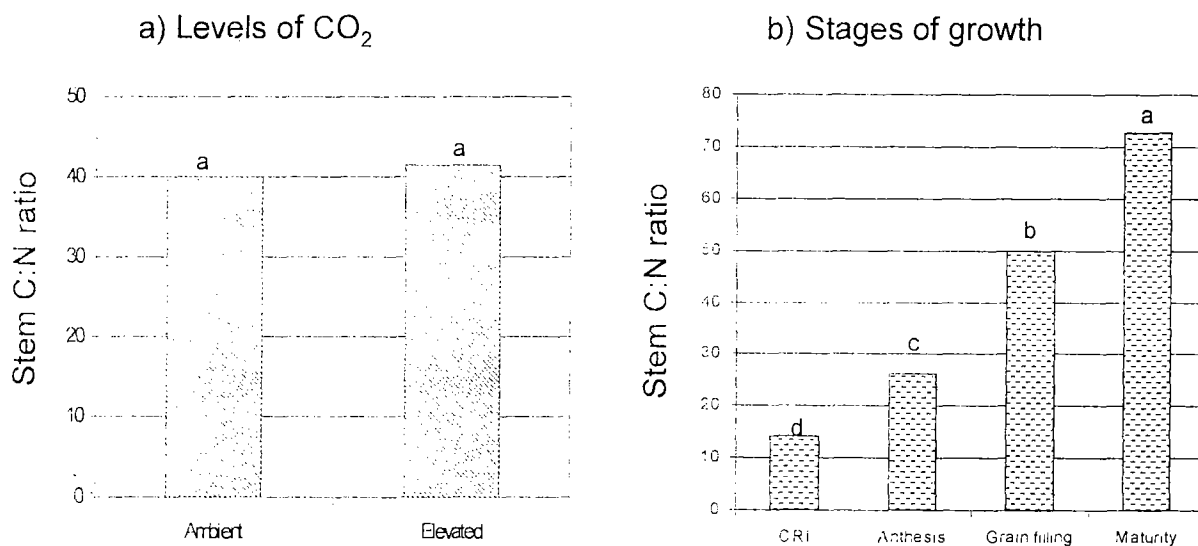


Fig. 58. The C:N ratio of the stem dry matter of wheat grown in OTC as influenced by:



The differences between values with any common alphabet in figures are not statistically significant and *vice versa*
 CRI: Crown root initiation

its value decreased with age of the crop (Fig. 57b). The C:N ratio of stem was not affected by higher CO₂ in atmosphere (Fig. 58a). As the crop progressed from CRI to maturity, C:N ratios increased significantly primarily owing to decrease in N content (Fig. 58b).

g) Nitrogen content and C:N ratio of leaf dry matter

The values pertaining to per cent nitrogen content and C:N ratio of wheat leaves as affected by levels of CO₂ and stages of crop growth are presented in Figures 59 and 60, respectively. Elevation of atmospheric CO₂ concentration decreased the average N concentration significantly by 0.79 per cent from 1.501 under ambient CO₂ (Fig. 59a). With age of the crop, leaf N concentration decreased significantly (Fig. 59b). Nevertheless, leaf C:N ratio was not affected by higher CO₂ in atmosphere (Fig. 60a), at every stage as the crop matured, its value increased significantly (Fig. 60b). Since C composition of wheat leaves did not change significantly (Fig. 49b), the increase in C:N ratio might be due to the decrease in N content of leaves with age.

h) Nitrogen content and C:N ratio of root dry matter

The values pertaining to per cent nitrogen content and C:N ratio of wheat roots as affected by levels of CO₂ and stages of crop growth are presented in Figures 61 and 62, respectively. The average N concentration in roots was not affected by the elevation of CO₂ concentration in atmosphere (Fig. 61a). However, its value decreased significantly with age of the crop from CRI to anthesis, and thereafter remained unchanged till maturity (Fig. 61b). The C:N ratio of root was not affected either by higher CO₂ in atmosphere (Fig. 62a). As the crop progressed from CRI to grain filling, C:N ratios decreased significantly due to the abrupt decrease in C concentration in roots between these stages (Fig. 62b). Later, an increase in C:N ratio was observed towards maturity.

i) Nitrogen content and C:N ratio of grains

The values pertaining to per cent nitrogen content and C:N ratio of wheat grains as affected by levels of CO₂ are presented in Figure 63 and 64, respectively. The average N concentration in grain did not change significantly as a result of elevation of CO₂ concentration in atmosphere. However a

Fig. 59. Nitrogen concentration (per cent) in the leaves of wheat grown in OTC as influenced by:

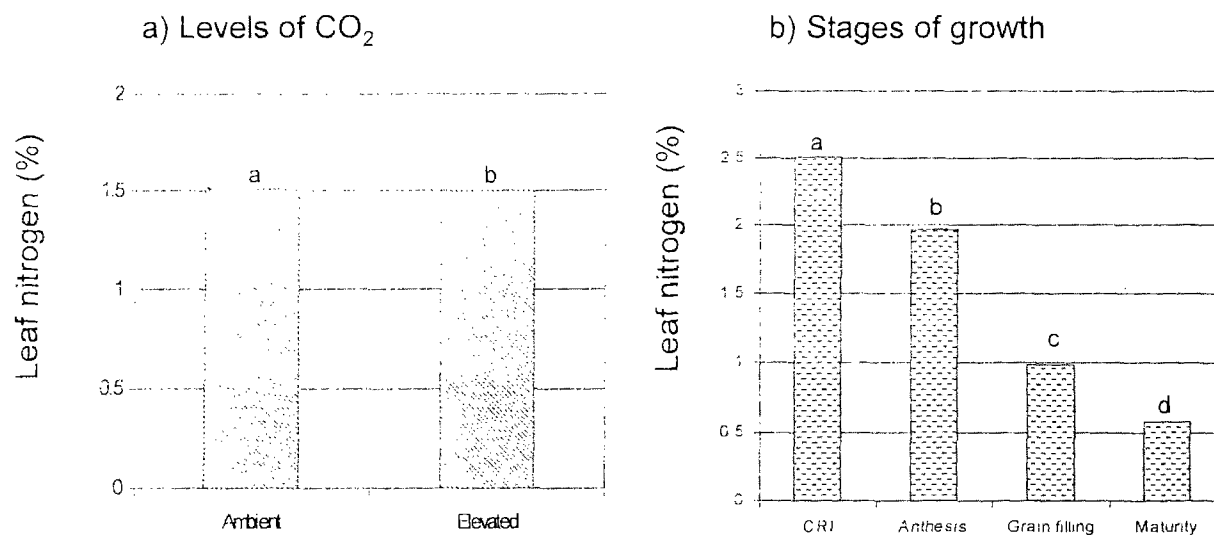
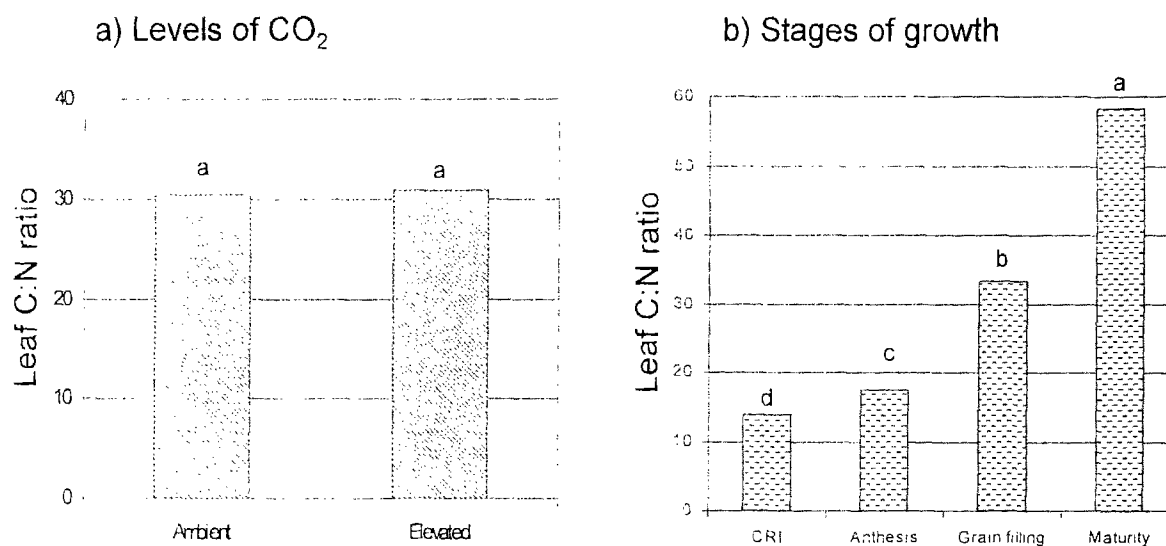


Fig. 60. The C:N ratio of the leaf dry matter of wheat grown in OTC as influenced by:



The differences between values with any common alphabet in figures are not statistically significant and *vice versa*

CRI: Crown root initiation

Fig. 61. Nitrogen concentration (per cent) in roots of wheat grown in OTC as influenced by:

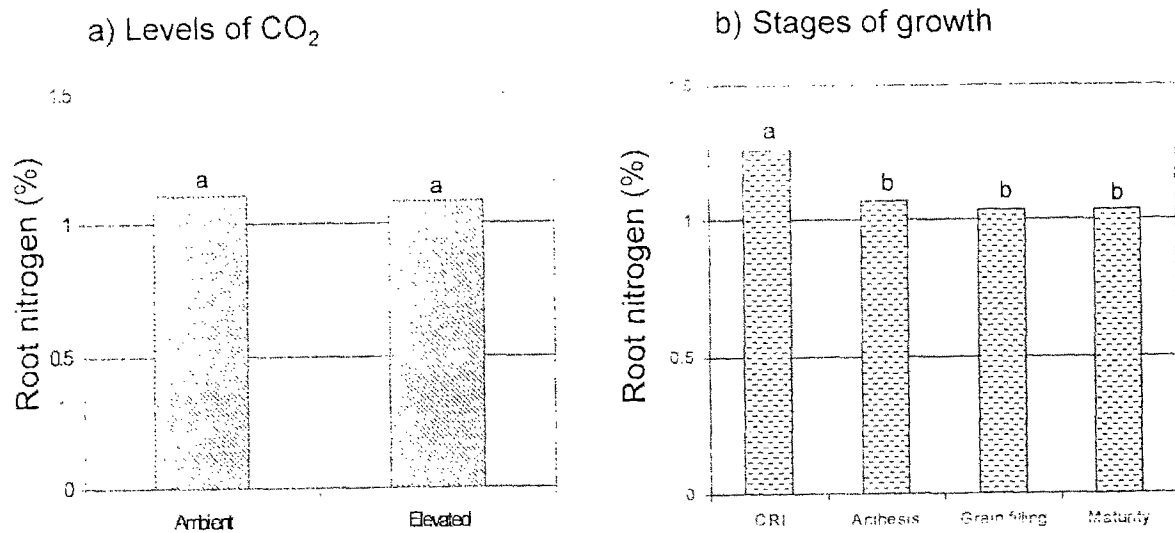
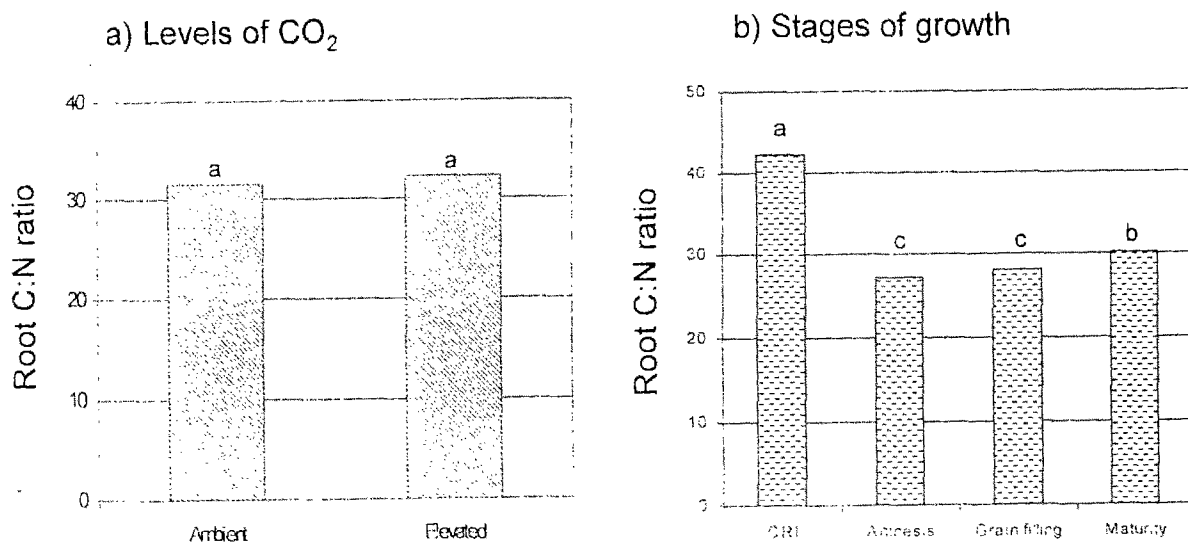


Fig. 62. The C:N ratio of root dry matter of wheat grown in OTC as influenced by:



The differences between values with any common alphabet in figures are not statistically significant and *vice versa*

CRI: Crown root initiation

Fig. 63. Nitrogen concentration (per cent) in the grains of wheat grown in OTC as influenced by the elevation of atmospheric CO₂ concentration

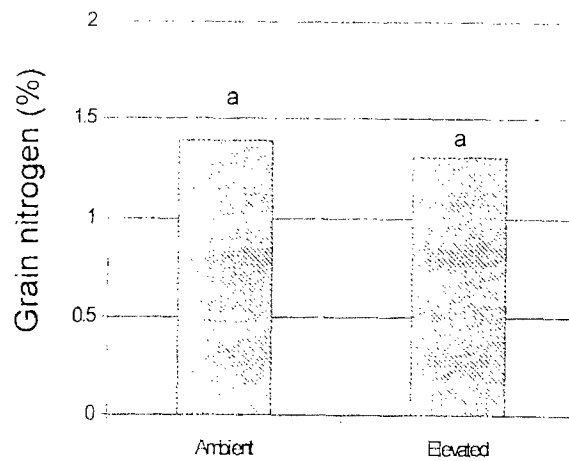
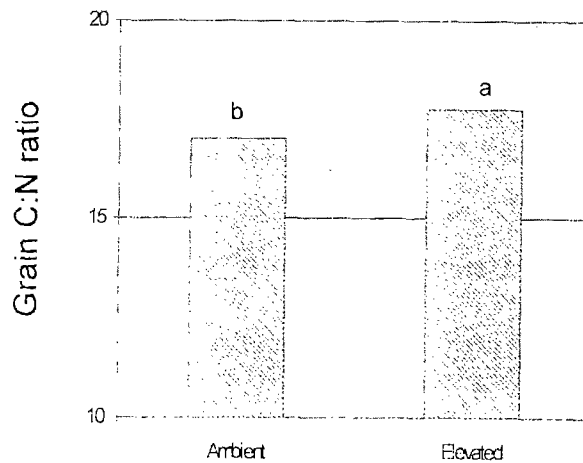


Fig. 64. The C:N ratio of the grains of wheat grown in OTC as influenced by the elevation of atmospheric CO₂ concentration



The differences between values with any common alphabet in figures are not statistically significant and *vice versa*

CRI: Crown root initiation

significantly higher C:N ratio was recorded in wheat grains when produced under elevated atmospheric CO₂ concentration compared to ambient condition.

4.1.2.2 Soil parameters

A. Carbon pools

a) Microbial biomass carbon (MBC)

The MBC having high turnover rate is one of the dynamic and labile phases of soil carbon. The average values of MBC in rhizosphere soil of wheat as affected by the levels of CO₂ and stages of wheat growth are given in the Figure 65. As a result of elevation of atmospheric CO₂, an increase in MBC content by 16.59 per cent was recorded in wheat rhizosphere soil (Fig. 65a). The amount of MBC in wheat rhizosphere was observed to be maximum at anthesis stage (Fig. 65b). Later as the crop approached maturity an abrupt decrease in MBC content was observed in rhizosphere soil and the value was lowest at maturity. Higher value of MBC associated with anthesis stage of crop might be due to the increased root dry matter observed at that stage which also denotes stage of maximum vegetative growth. After anthesis, the crop entered the reproductive phase and decay of roots started, hence causing a decrease in microbial biomass carbon in crop rhizosphere. Moreover, preferential translocation of photosynthates to the reproductive parts might also have reduced the exudation from roots towards maturity, leading to a decrease in microbial activity during the reproductive phase of crop growth.

Interaction effect of the levels of CO₂ with stages of growth was also significant and values are presented in Table 35. At all stages of wheat growth (except maturity), MBC contents under elevated CO₂ were higher than the corresponding values under ambient CO₂. Highest value of MBC in wheat rhizosphere soil was observed at anthesis stage under elevated CO₂. This was followed by CRI stage under elevated and anthesis under ambient CO₂ in sequence. There was no significant difference between the CRI and anthesis stages of wheat growth with respect to MBC in crop rhizosphere under ambient CO₂. In other words, while the MBC contents in wheat rhizosphere soil decreased as the crop grew from CRI to anthesis under elevated CO₂, the

Fig. 65. Microbial biomass carbon (MBC, mg kg⁻¹) in wheat rhizosphere soil at OTC as influenced by:

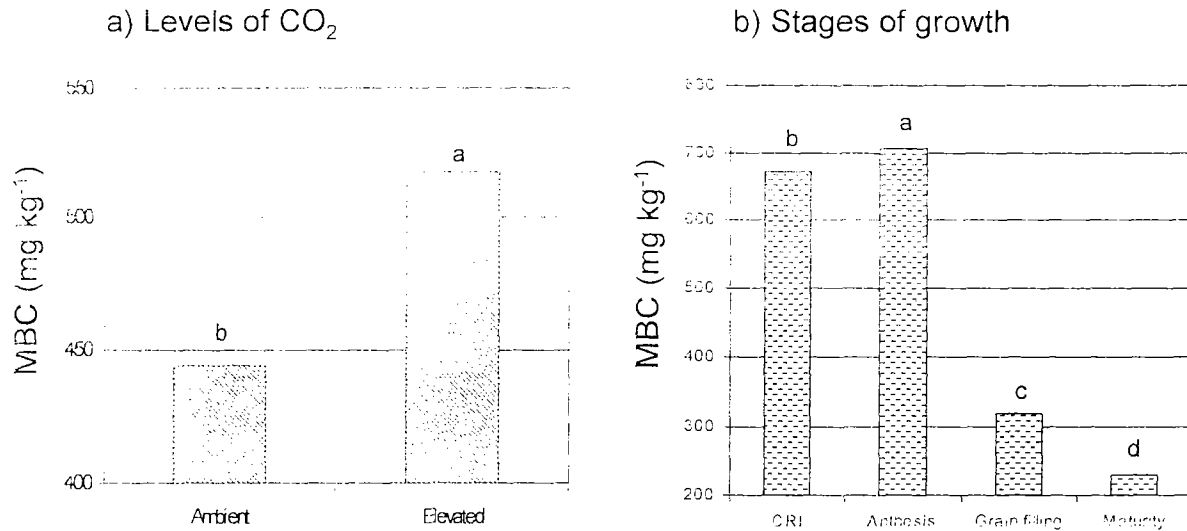


Table 35. Microbial biomass carbon (MBC, mg kg⁻¹) in wheat rhizosphere soil at OTC as influenced by the interaction of levels of CO₂ and stages of crop growth

Growth stages	Levels of CO ₂	
	Ambient	Elevated
CRI	627.9 ^c	714.1 ^b
Anthesis	641.4 ^c	772.1 ^a
Grain filling	288.5 ^e	347.5 ^d
Maturity	218.2 ^f	238.3 ^f

The differences between values with any common alphabet in figures or table are not statistically significant and *vice versa*

CRI: Crown root initiation

value did not change significantly between the two stages under ambient CO₂ condition.

b) Dissolved organic carbon (DOC)

Average values of DOC as functions of levels of CO₂ and stages of crop growth are recorded in Figure 66. Elevation of atmospheric CO₂ from 372 to 600 $\mu\text{mol mol}^{-1}$ has caused an increase in average DOC content in wheat rhizosphere by 17.36 per cent (Fig. 66a) In absolute terms, the value increased from 117.5 mg kg⁻¹ under ambient to 137.9 mg kg⁻¹ under elevated CO₂. The DOC primarily comprises of low molecular weight substances generally associated with the passive secretions through root cells. Higher root growth observed under elevated CO₂ might have contributed to the higher values of DOC.

Regarding stages of crop growth, as in case of rice, DOC was maximum at CRI, and further its values decreased significantly as the crop approached maturity (Fig. 66b). At CRI, absence of secondary cell wall might have helped more leakage as exudation of carbonaceous substances from root cells, thus leading to higher values of DOC in crop rhizosphere.

Interaction between CO₂ levels and stages of growth was also significant and the values are presented in Table 36. The DOC content in wheat rhizosphere soil was observed to be highest at CRI under elevated CO₂ condition. This was followed by the value at anthesis under elevated CO₂, which was on par with the value at CRI under ambient CO₂. After anthesis stage, under elevated CO₂, DOC contents in soil significantly reduced as the crop approached maturity. However under ambient CO₂ concentration, the decrease in DOC from grain filling to maturity was not significant. Thus, under elevated CO₂, there was a significant difference between anthesis and maturity, which was not observed under ambient CO₂ condition. Nevertheless, at all stages of crop growth DOC contents in rhizosphere were higher under elevated CO₂ in comparison to the corresponding values under ambient CO₂.

c) Carbohydrate carbon (CHC)

The main effects of levels of CO₂ and growth stages on carbohydrate carbon (CHC) contents in wheat rhizosphere soil are depicted in Figure 67. As the level of CO₂ was increased in crop atmosphere, an increase in average

Fig. 66. Dissolved organic carbon (DOC, mg kg⁻¹) in wheat rhizosphere soil at OTC as influenced by:

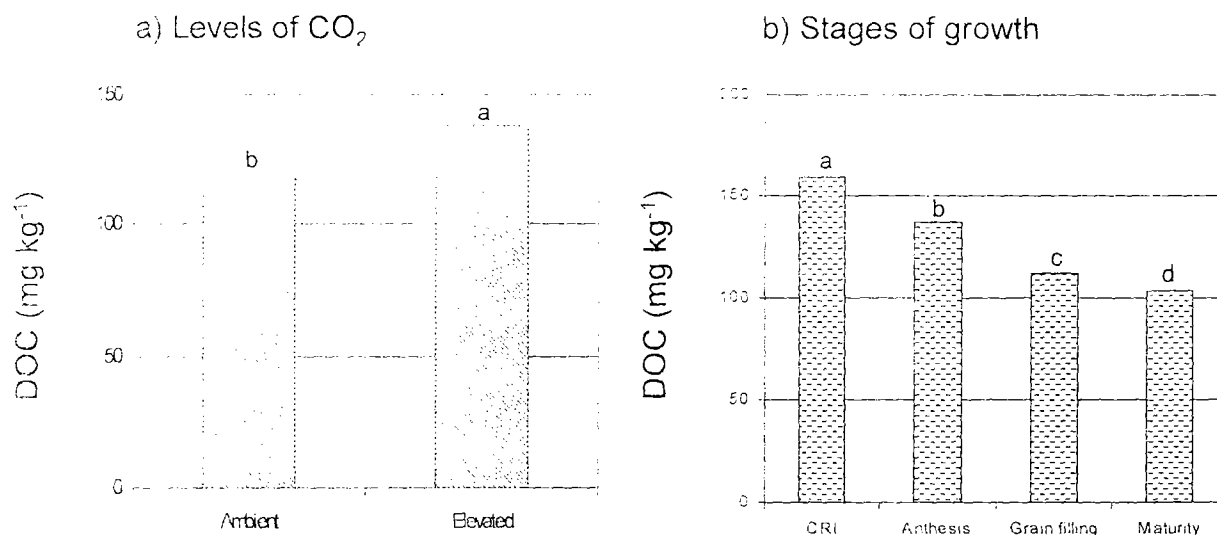


Table 36. Dissolved organic carbon (DOC, mg kg⁻¹) in wheat rhizosphere soil at OTC as influenced by the interaction of levels of CO₂ and stages of crop growth

Growth stages	Levels of CO ₂	
	Ambient	Elevated
CRI	147.6 ^b	170.5 ^a
Anthesis	126.0 ^c	147.7 ^b
Grain filling	101.1 ^e	122.1 ^c
Maturity	95.13 ^e	111.3 ^d

The differences between values with any common alphabet in figures or table are not statistically significant and *vice versa*

CRI: Crown root initiation

CHC content by 7.87 per cent was observed in wheat rhizosphere (Fig. 67a). The CO₂-stimulated increase in biomass, root growth and translocation of biomass to underground portions as described earlier might have contributed to the increased values of CHC under high CO₂.

With regard to stages of growth, average CHC content was lowest at CRI stage (2115 mg pot⁻¹), which further increased to 2954 mg pot⁻¹ as the crop approached maturity (Fig. 67b). There were significant increases between stages with respect to CHC values indicated by different Duncan values in superscript. The increase in CHC value towards final stages of crop growth can be ascribed to the contribution from structural carbohydrate of the root cells released into soil on their lysis.

The data of CHC contents in wheat rhizosphere related to the interaction of CO₂ levels and stages of wheat growth are shown in Table 37. The interaction was significant and higher values were recorded under elevated CO₂ at all stages of growth except CRI. Highest CHC (3181 mg kg⁻¹) in rhizosphere soil was observed at maturity stage of wheat growth under elevated CO₂ condition. This was followed by the CHC content at maturity under ambient CO₂. The anthesis and grain filling stages did not differ significantly under either levels of CO₂. The extent of increase in values with age of wheat crop was maximum between grain filling and maturity stage under both elevated and ambient CO₂ conditions. This further enforces the speculation that the increased decay and lysis of the profuse root system act as the primary source of CHC pool in soil.

d) Labile carbon (LBC)

The labile carbon (LBC, 0.33 M KmnO₄ oxidizable) contents in wheat rhizosphere soil as influenced by levels of CO₂ and stages of growth are depicted in Figure 68. Elevation of atmospheric CO₂ increased the average LBC content in wheat rhizosphere soil by 7.51 per cent as the value increased from 2092 to 2249 mg kg⁻¹ (Fig. 68a).

As the crop grew from CRI to maturity, there was an increase in LBC contents in rhizosphere soil (Fig. 68b). The highest value was associated with maturity and the lowest with CRI stage. The grain filling and maturity stages of wheat growth did not differ significantly with respect to the average LBC

Fig. 68. Labile carbon (LBC, mg kg⁻¹) in wheat rhizosphere soil at OTC as influenced by:

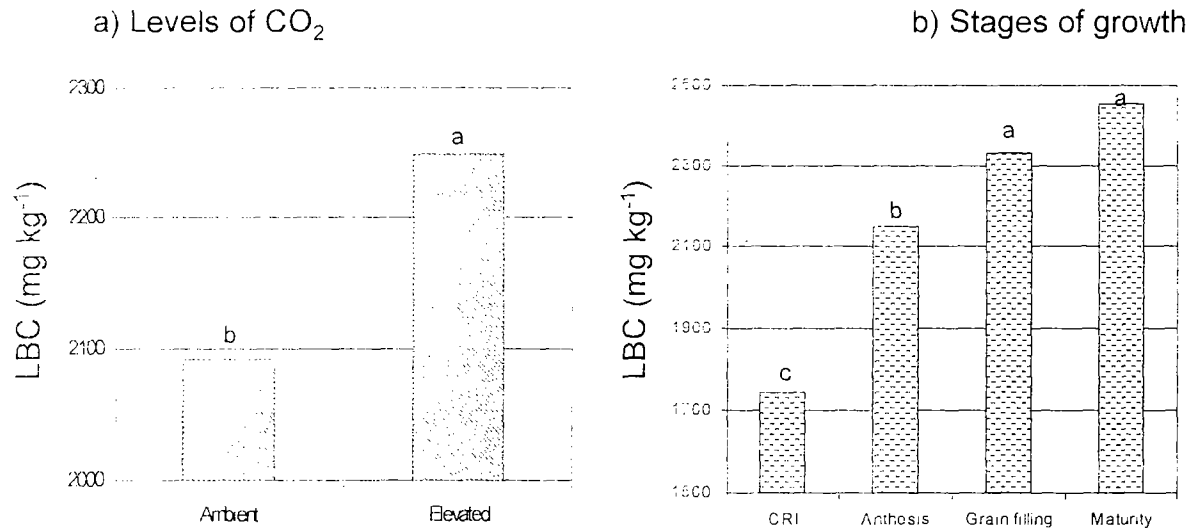


Table 38. Labile carbon (LBC, mg kg⁻¹) in wheat rhizosphere soil at OTC as influenced by the interaction of levels of CO₂ and stages of crop growth

Growth stages	Levels of CO ₂	
	Ambient	Elevated
CRI	1678 ^f	1808 ^e
Anthesis	2062 ^d	2238 ^c
Grain filling	2234 ^c	2433 ^{ab}
Maturity	2393 ^b	2517 ^a

The differences between values with any common alphabet in figures or table are not statistically significant and *vice versa*

CRI: Crown root initiation

contents. The large increase in LBC contents in soil during CRI to anthesis can be attributed to the increased root activity and exudation of organic substances. Higher values of LBC content in soil towards maturity can be explained by lysis and degradation of the root mass.

Interaction effect was significant with higher values of LBC in rhizosphere soil under elevated CO_2 at all stages of wheat growth (Table 38). With age of the crop, there was a continuous and significant increase in LBC value under ambient CO_2 concentration, while under elevated CO_2 the increase in value between grain filling and maturity stages was not statistically significant.

e) Total soil carbon (TSC)

Total soil carbon (TSC) content in wheat rhizosphere soil as affected by elevation of CO_2 and stages of growth are presented in Table 39. Increase in atmospheric CO_2 concentration did not affect the total carbon content in soil. Stages of crop growth also had no significant effect on TSC values.

Interaction was also non significant. No detectable change was observed with respect to the initial status also.

B. Inorganic nitrogen pools

a) Ammoniacal nitrogen

Main effects of CO_2 and growth stages on ammoniacal nitrogen in wheat rhizosphere soil are depicted in Figure 69. Elevation of atmospheric CO_2 did not affect this pool of inorganic nitrogen (Fig. 69a). Nevertheless, with age of the crop decrease in its value was observed (Fig. 69b). Two-way interaction was also not significant (Table 40).

b) Nitrate nitrogen

Main effects of CO_2 and growth stages on nitrate nitrogen in wheat rhizosphere soil are depicted in Figure 70. As the level of CO_2 was increased in crop atmosphere, a decrease in average $\text{NO}_3\text{-N}$ by 11.76 per cent was observed in wheat rhizosphere (Fig. 70a). The CO_2 -stimulated increase in biomass, root growth and translocation of biomass to underground portions might have resulted in increased rate of uptake of $\text{NO}_3\text{-N}$ by the crop thus depleting the pool from soil.

Table 39. Total soil carbon (TSC, g kg⁻¹) in wheat rhizosphere soil at OTC as influenced by elevated CO₂ at different stages of growth

Growth stages	Levels of CO ₂		Mean
	Ambient	Elevated	
CRI	7.22 ^c	7.39 ^c	7.31 ^B
Anthesis	7.36 ^c	7.63 ^{bc}	7.49 ^B
Grain filling	7.57 ^{bc}	7.68 ^{abc}	7.63 ^B
Maturity	8.03 ^{ab}	8.21 ^a	8.12 ^A
Mean	7.55 ^A	7.73 ^A	

The differences between values with any common alphabet in table are not statistically significant and *vice versa*

Values pertaining to the means related to a parameter (stages of crop growth or levels of CO₂) are to be compared among themselves only

CRI: Crown root initiation

Fig. 69. Ammoniacal nitrogen (mg kg^{-1}) in wheat rhizosphere soil as influenced by:

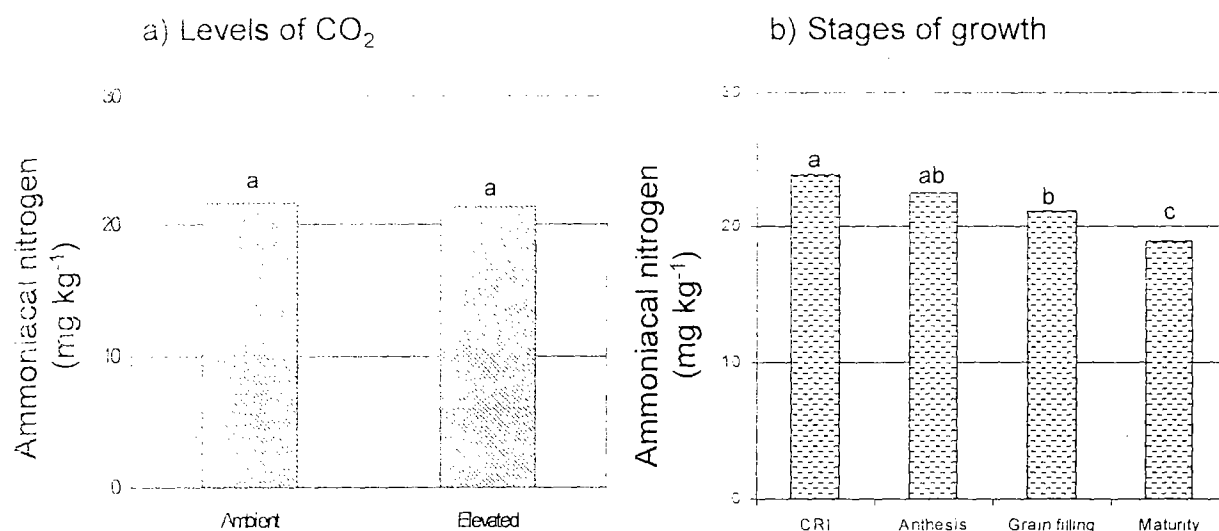


Table 40. Ammoniacal nitrogen (mg kg^{-1}) in wheat rhizosphere soil as influenced by the interaction of levels of CO_2 and stages of crop growth

Growth stages	Levels of CO_2	
	Ambient	Elevated
CRI	23.99 ^a	23.64 ^a
Anthesis	22.84 ^a	22.41 ^a
Grain filling	21.43 ^a	20.81 ^a
Maturity	19.04 ^a	18.66 ^a

The differences between values with any common alphabet in figures or table are not statistically significant and vice versa

CRI: Crown root initiation

Fig. 70. Nitrate nitrogen (mg kg^{-1}) in wheat rhizosphere soil at OTC as influenced by:

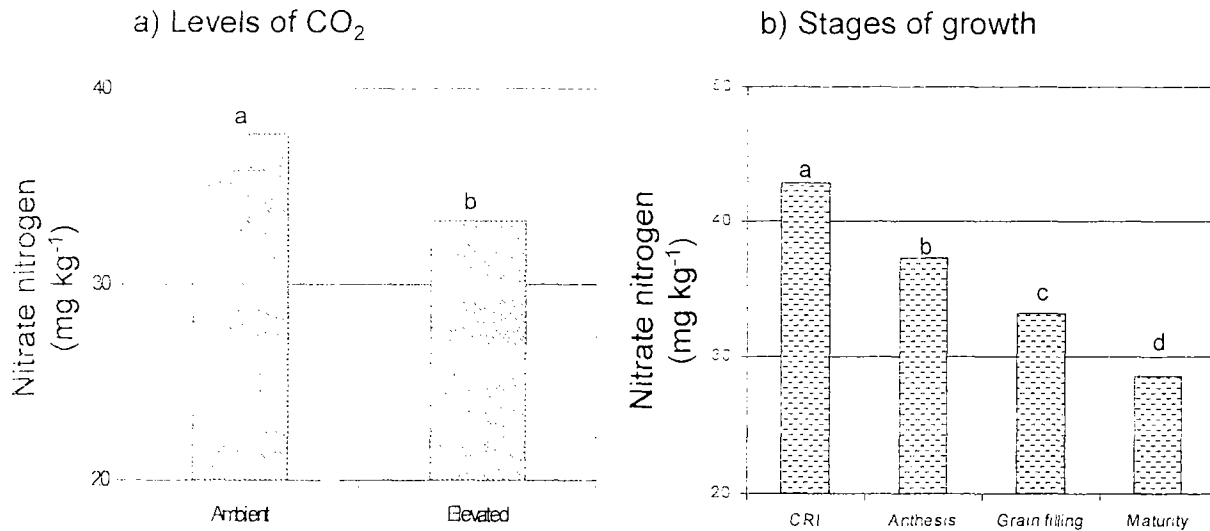


Table 41. Nitrate nitrogen (mg kg^{-1}) in wheat rhizosphere soil at OTC as influenced by the interaction of levels of CO₂ and stages of crop growth

Growth stages	Levels of CO ₂	
	Ambient	Elevated
CRI	45.44 ^a	40.21 ^b
Anthesis	39.45 ^b	35.14 ^c
Grain filling	35.78 ^c	30.52 ^d
Maturity	29.92 ^d	27.11 ^e

The differences between values with any common alphabet in figures or table are not statistically significant and *vice versa*

CRI: Crown root initiation

With regard to stages of growth, the amount of $\text{NO}_3\text{-N}$ in soil was highest at CRI stage and thereafter decreased with age of the crop, owing to uptake by the crop (Fig. 70b). All four stages of wheat growth differed significantly with respect to this pool of inorganic nitrogen.

Interaction between CO_2 levels and stages of growth was also significant and the values are presented in Table 41. $\text{NO}_3\text{-N}$ content in wheat rhizosphere soil was observed to be highest at CRI under ambient CO_2 condition. This was followed by the value at CRI under elevated CO_2 , which was on par with the value at anthesis under ambient CO_2 concentration. Similarly, the value at anthesis stage under elevated CO_2 was on par with the value at grain filling under ambient CO_2 . Grain filling stage under elevated CO_2 and maturity stage under ambient CO_2 also did not exhibit significant difference. At all stages of crop growth $\text{NO}_3\text{-N}$ content in wheat rhizosphere was lower under elevated CO_2 in comparison to the corresponding values under ambient CO_2 .

4.1.3 Gains in active carbon pools in rice and wheat rhizospheres

An increase in all active carbon pools has been recorded in the rhizosphere soils of rice and wheat in response to the elevation of atmospheric CO_2 concentration. However, rhizosphere soils of the two crops differed with respect to the nature of effect on active carbon pools.

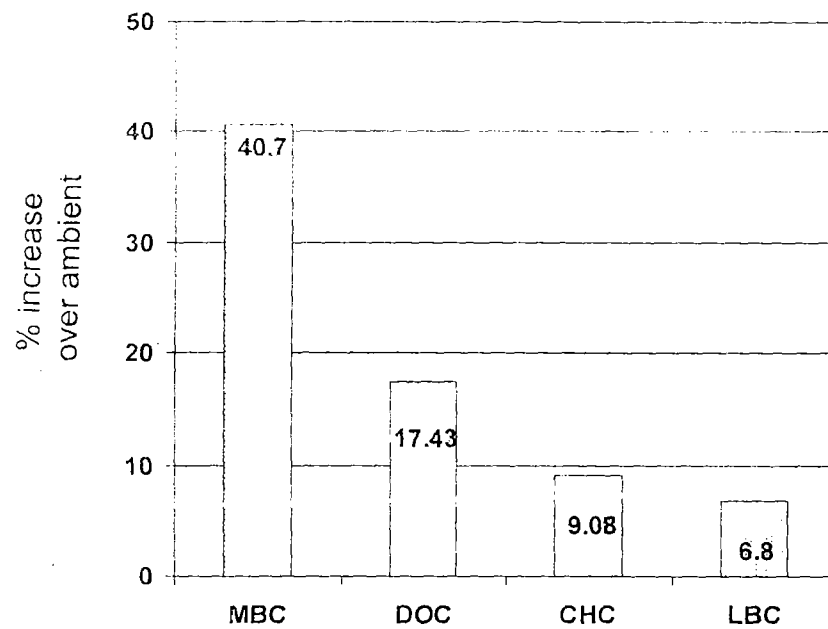
Average gains in the active carbon pools due to elevation of CO_2 concentration in rice and wheat crop atmosphere are presented in Figure 71. Among the four pools studied, MBC in rhizosphere soil of rice encountered maximum benefit recording a 40.7 per cent increase over the ambient treatment. The gain in DOC contents was by 17.4 per cent, which was next only to MBC.

In case of wheat, the order of gain in various carbon pools got reversed. In this case gain was maximum in DOC content, which recorded a 17.4 per cent increase. The MBC content in wheat rhizosphere soil was increased by 16.6 per cent and the extent of gain was next only to DOC.

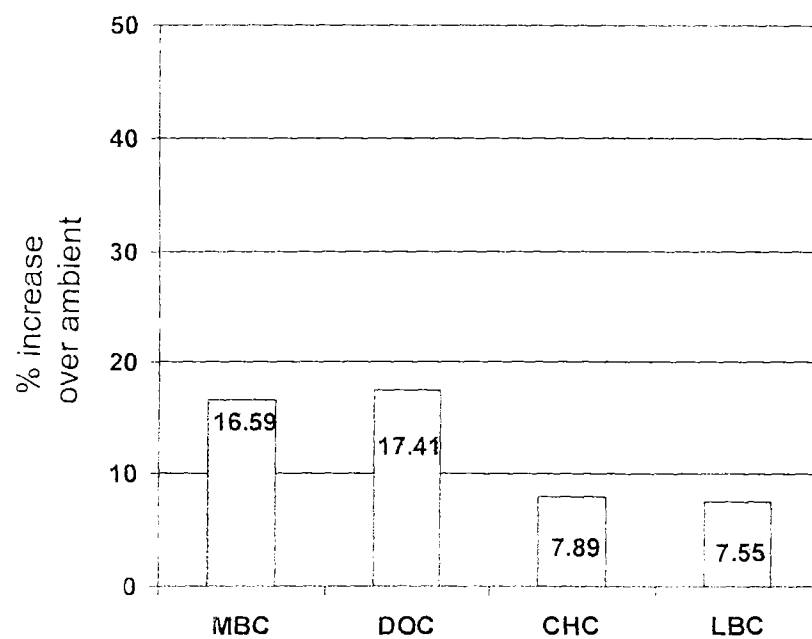
MBC represents the carbon associated with living microbes. The higher values of MBC in rhizosphere soil under elevated CO_2 indicate the increased proliferation of microbial growth in this situation. Elevation of CO_2

Fig. 71. Per cent increase in different carbon fractions in the rhizosphere soils of both crops as influenced by elevation of CO₂ when grown in OTC

a) Rice



b) Wheat



concentration in atmosphere was found to increase the root growth in rice crop whose contribution by secretions or degradation might have led to the increase of MBC in rhizosphere.

DOC comprises of low molecular weight substances including short chain sugars, amino acids, carboxylic acids; and these are the exudation products from the young metabolically active roots. Since the root mass was higher under elevated CO₂ condition DOC was also expected to increase. These two pools of carbon represent most labile fractions (among the recorded pools) and are very sensitive to the changes in management or agronomic practices. Hence these changes were expected.

CHC contents in rhizosphere soils of rice and wheat were occupying the third position in the order of gain among the four active carbon pools. The CHC experienced a gain of 9.08 per cent in rice rhizosphere and 7.89 per cent in wheat rhizosphere. Carbohydrate C represents primarily the structural carbon and other carbohydrate substances in root exudates. It is relatively less labile in comparison to MBC or DOC.

LBC is relatively resistant among the four carbon pools studied. Elevation of atmospheric CO₂ increased LBC contents by 6.8 per cent in rice rhizosphere and by 7.55 per cent in wheat rhizosphere. Labile carbon represents the pool of soil carbon that is oxidized by 0.333 *M* KMnO₄ and is comprised of the relatively resistant yet easily oxidisable fraction. It consists of certain fractions of DOC, CHC and LBC as well. Hence an increase in LBC content in rhizosphere soil in response to higher CO₂ was probably a consequence of increase observed in all the other three pools.

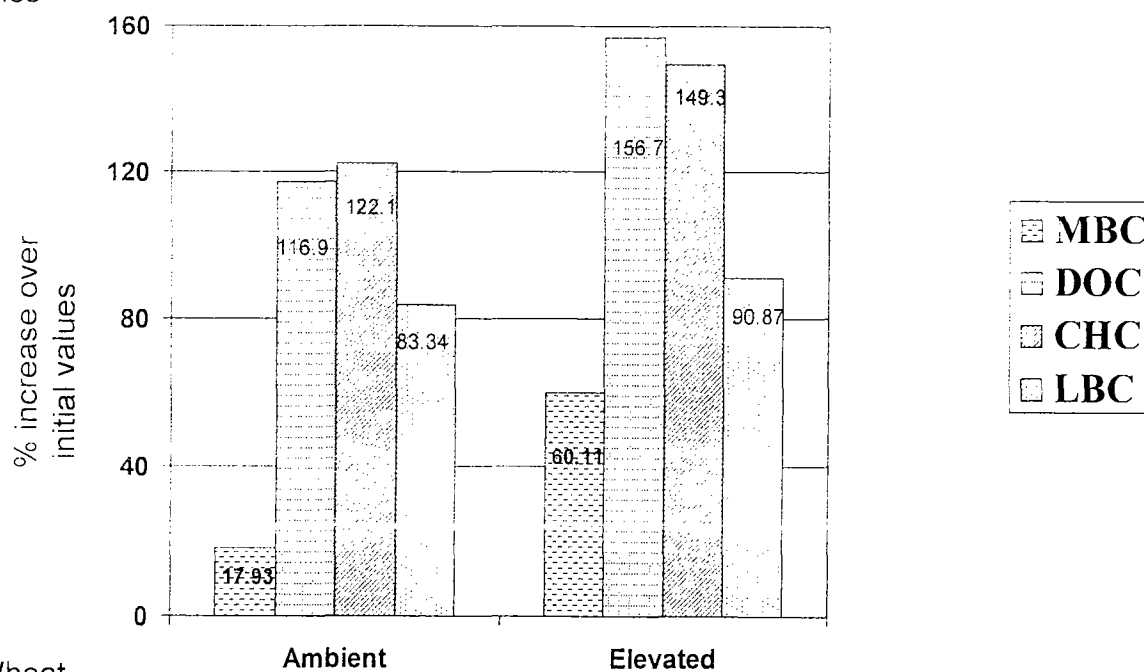
4.1.4 Relative build up of active carbon pools in rice and wheat rhizospheres

Increase in all active carbon pools with relation to their initial status was observed in the rhizosphere soils of both rice and wheat. The relative build up of the active carbon pools; MBC, DOC, CHC and LBC in the rhizosphere soils of both crops under ambient and elevated atmospheric CO₂ conditions are depicted in Figures 72 and 73.

In Figure 72, the bar diagram represents the values of the C pools at the end of the respective crop expressed as per cent increase over their initial

Fig. 72. Relative increase (per cent over initial values) in different carbon pools in rhizosphere soils in OTC at the end of respective crops as affected by elevation of CO₂

a) Rice



b) Wheat

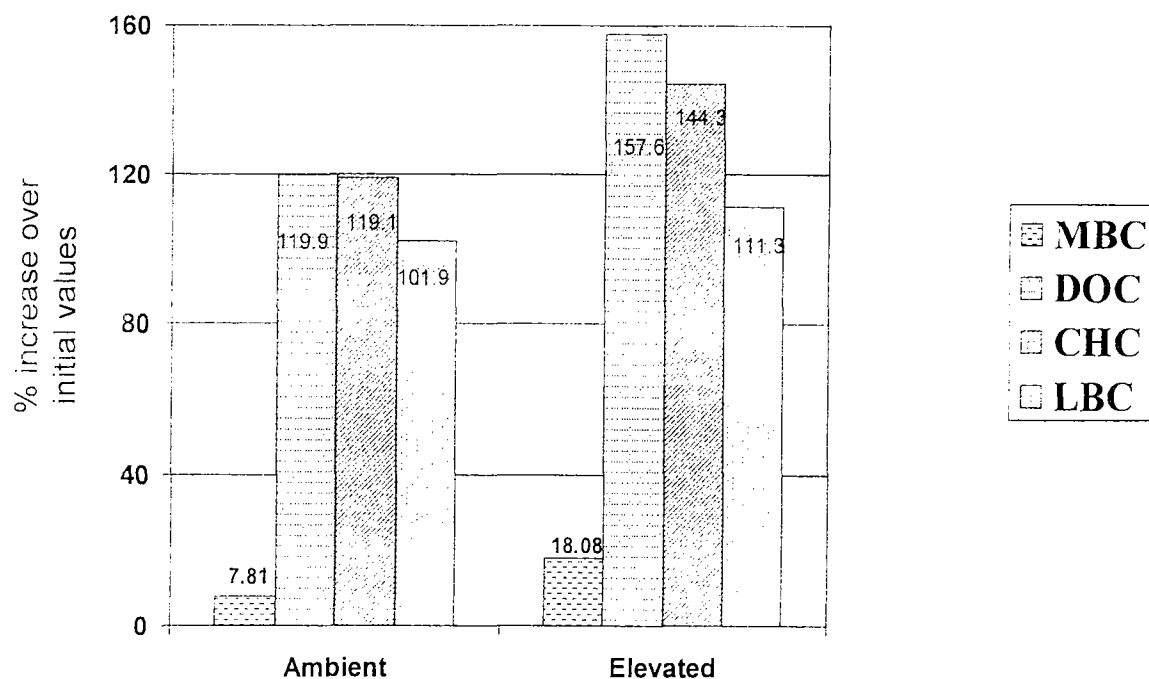
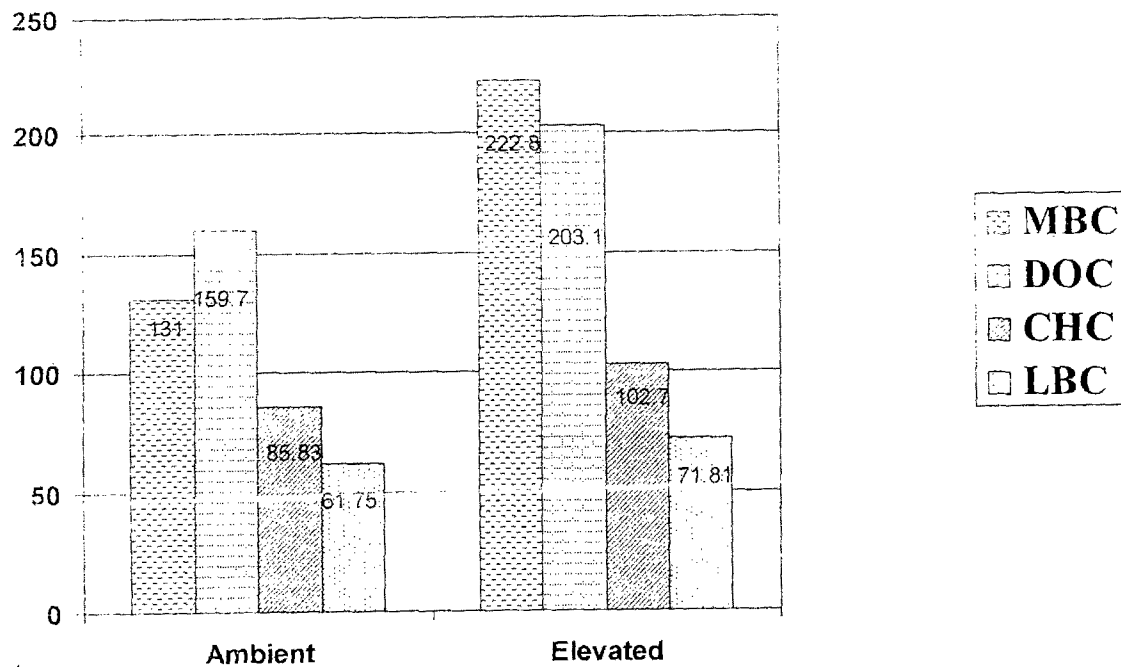
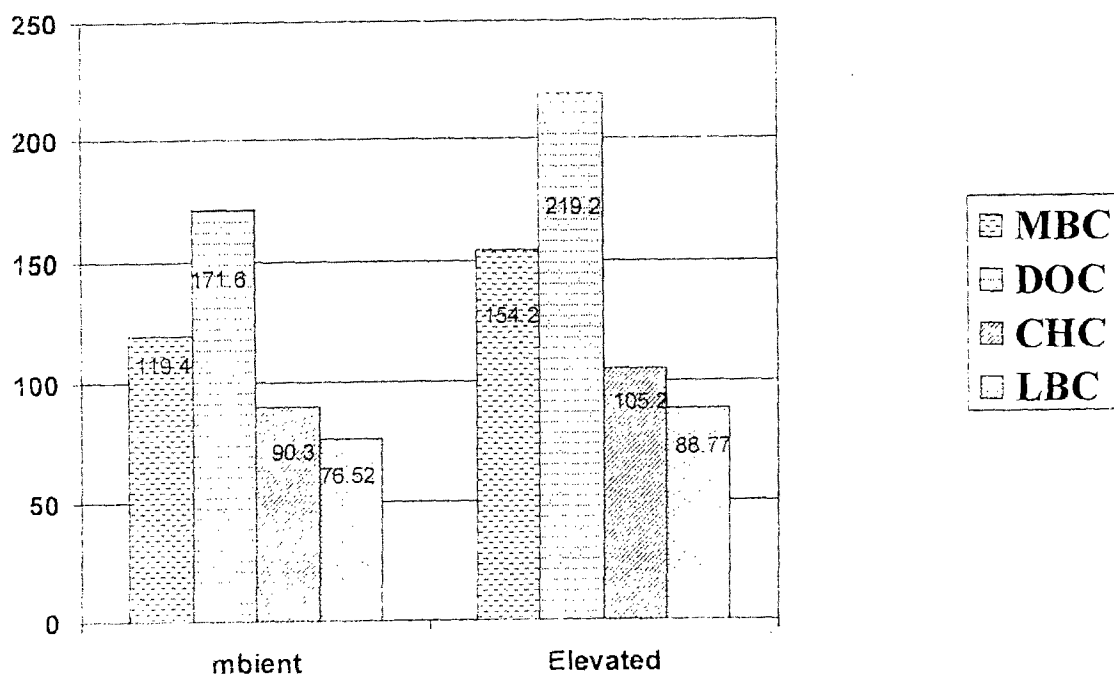


Fig. 73. Relative increase (per cent) in different active carbon pools (averaged over all the crop growth stages) in rhizospheres of the test crops as affected by elevation of CO₂

a) Rice



b) Wheat



status, while in Figure 73, gain in relation to the average values of the carbon pools are expressed.

The relative accumulation of all active carbon pools was higher under elevated atmospheric CO₂ concentration in rhizospheres of both the crops. The MBC was found to increase by 17.93 per cent over its initial value in rice rhizosphere under ambient CO₂, while it increased by 60.11 per cent under elevated CO₂ concentration. As a result of elevation of CO₂ the per cent build up of DOC increased from 116.9 to 156.7. In case of CHC, its increase over initial content was 122.1 and 149.3 per cent under ambient and elevated CO₂, respectively. LBC increased by 83.34 per cent over its initial value under ambient CO₂, while under elevated CO₂ it increased by 90.87 per cent.

Figure 73 represents the build up of the active carbon pools in rice and wheat rhizospheres when the average values of the pools (averaged over all growth stages) were expressed in relation to their initial values. The relative build up was found to be more in MBC and DOC as their gain was greater than CHC and LBC.

4.1.5 Interrelations between plant and soil parameters

Stepwise regression was performed to find out the relationships of the active carbon and inorganic nitrogen pools with plant related parameters. The analysis would help us to identify the key plant characteristics that contribute to the active carbon and inorganic nitrogen pools in crop rhizosphere soil. The data pertaining to rice and wheat were clubbed together and the analysis was performed. Altogether eight plant related parameters were chosen as the predictor variables. They were: N concentration in root (A), Root dry weight (B), Root volume (C), per cent carbon allocated belowground to root (D), C concentration in root (E), per cent biomass allocated belowground (F) total carbon uptake (G) and root C uptake. Regression analysis was done taking each of the carbon and nitrogen pools one at a time as the dependent variable. Stepwise regression equations of the dependent variables as functions of predictor variables are given in Table 42. Stepwise regression allows for the inclusion of the key predictor variables only, thus permitting omission of unrelated variables. Out of the eight plant related parameters,

seven were found to be related to at least one of the carbon and nitrogen pools.

In case of MBC, the four variables namely, N concentration in root, root volume, per cent C allocation belowground by the crop and root weight were found to explain 95 per cent of the variation in its values. MBC was positively related to root N concentration, root volume and per cent carbon allocated belowground; while root weight had a negative effect. All the root related parameters are likely to have positive influence on microbial biomass as they contribute substrates for microbial growth both in form of secretions and degradation/lysis products. Hence, negative relationship with root weight was not quite expected. The only reason, which could be speculated is the competitive inhibition with root growth for high demand of nutrients.

Regarding DOC, carbon and nitrogen contents in root and per cent biomass allocated belowground were found to explain 82 per cent of the variation in its data. All four variables were found to contribute positively to the variation in DOC. This pool of active carbon comprises of low molecular weight sugars and amino acids and are leaked out from young root cells devoid of secondary cell wall. The exudation from roots is dependent on its carbon and nitrogen composition, which is a measure of the uptake. Translocation of photosynthates to underground portions is a major factor, which determines the rate and type of exudation from roots. Hence no wonder that these variables have played a positive role in explaining the variability in DOC contents in rhizosphere soil.

The carbohydrate carbon (CHC) content in rhizosphere soil was influenced positively by N concentration in roots, total C uptake, per cent C allocated belowground and negatively by root weight. Since CHC is the C pool mainly composed of the structural carbohydrates originating from the degradation of root cells, the positive relation with the three parameters is naturally expected. The CHC can have negative relation with root weight as it is released into soil during the decay of root cells. A negative relation with the per cent C allocated belowground was also explainable. Higher root weight or per cent C allocated belowground indicate lower rate of decay of root cells resulting in lower values of CHC in rhizosphere soil.

The variation in LBC was predicted to 85 per cent by the positive relation with total C uptake and the negative relation with per cent C allocated belowground. LBC is not an exclusively separate pool of carbon. It includes certain fractions of the other three pools of active carbon. The contribution from MBC to LBC is directly affected by total C uptake by plants. Dissolved organic carbon is dependent on the root activity and exudation, which is also direct function of C uptake. Hence LBC is expected to be positively related to C uptake. Since CHC is the fraction that is released into soil during the decay of root cells, its contribution to LBC is expected to be negatively related to the per cent C allocated belowground.

Ammoniacal N pool was positively affected by the per cent biomass translocated belowground by the crops. It could explain 85 per cent of the variation in data. When higher plant biomass is allocated belowground, it gives more of organic mass to be incorporated in soil. Ammoniacal nitrogen being the first mineralized form of N, might have thus been related to this parameter.

Nitrate nitrogen was found to be positively influenced by the N concentration in roots of rice and wheat. Increase in root N concentration is likely to improve C:N ratio of root mass, specially in view of the observed widening of the ratio under elevated CO₂ condition. Hence, improvement in C:N ratio might increase degradability of incorporated root mass, thus influencing NO₃-N content in rhizosphere.

There was no common variable appearing in all regression equations. The per cent C allocated belowground explained the variations in MBC, CHC and LBC to some extent. It was negatively related to CHC and LBC as they are released during the decay of root cells. The positive relation of MBC with the variable is due to the proliferation of microbes in response to increased root exudation. The N concentration in roots contributed to the variations in MBC, DOC, CHC and NO₃ pools in soil.

4.2 FIELD EXPERIMENT – RICE AND WHEAT

Rice and wheat crops were grown in wet (*kharif*) and winter (*rabi*) seasons of 2004-20005. The soil samples were collected from different depths at four different physiological stages of growth and analysed for

different parameters. The results of the experiment conducted in IARI field utilizing the FACE facility are detailed under the following headings and sub headings:

4.2.1 Rice crop

- a) Microbial biomass carbon
- b) Dissolved organic carbon
- c) Carbohydrate carbon
- d) Labile carbon
- e) Total soil carbon

4.2.2 Wheat crop

- a) Microbial biomass carbon
- b) Dissolved organic carbon
- c) Carbohydrate carbon
- d) Labile carbon
- e) Total soil carbon

4.2.3 Gains in carbon pools

4.2.4 Relative build up of active carbon pools

4.2.1 Rice crop

a) Microbial biomass carbon (MBC)

Microbial biomass carbon is one of the dynamic and labile phases of soil carbon. The average values of MBC in soil during rice crop as individually influenced by the levels of CO₂, stages of crop growth and depth of soil are given in Figure 74.

As a result of elevation of atmospheric CO₂, MBC content in field soil increased by more than eighteen per cent (Fig. 74a).

Microbial biomass carbon content in soil was found to be maximum at flowering stage. Later as the crop progressed towards maturity, a greater decrease in MBC content was observed. This could be due to the decay of roots of rice in the reproductive phase of growth (Fig. 74b).

Microbial biomass carbon decreased down the soil profile from 0 to 20 cm (Fig. 74c). As a matter of fact, this decrease in MBC was due to lesser influence of rhizosphere and root exudates on soil carbon and microbial activity.

Fig. 74. Microbial biomass carbon (MBC, mg kg^{-1}) in soil during rice growth under FACE as influenced by the main effects of:

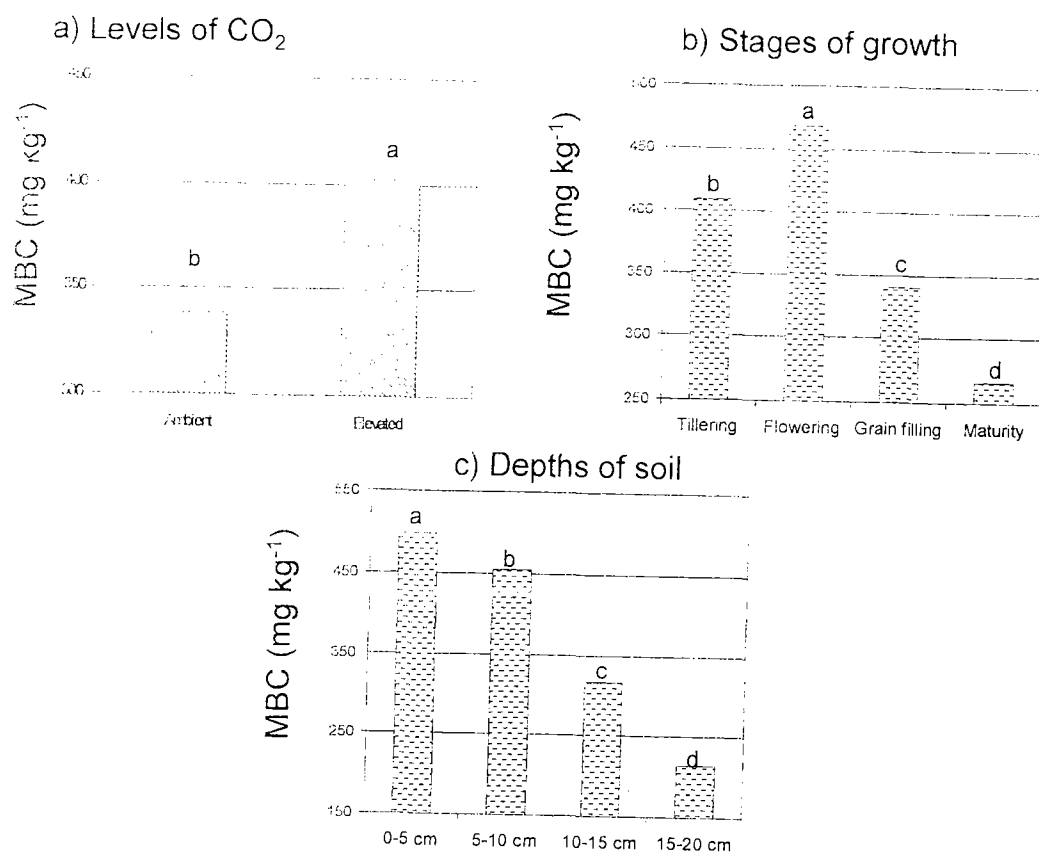
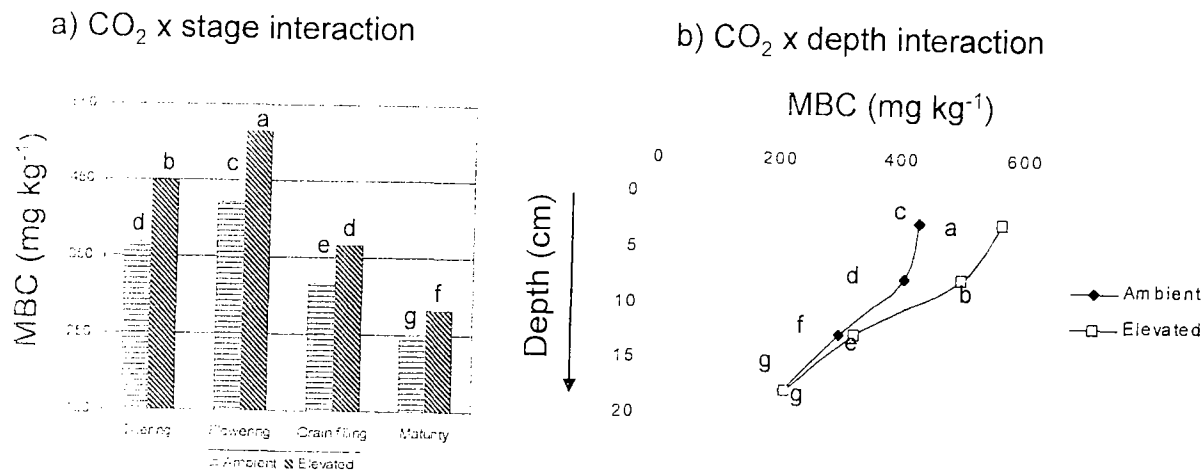


Fig. 75. Microbial biomass carbon (MBC, mg kg^{-1}) in soil during rice growth as affected by :



The differences between values with any common alphabet in figures are not statistically significant and *vice versa*

The mutual interactions of the levels of CO₂ with stages of growth and with depth of soil were also significant and values are presented in Figure 75. At all stages of rice growth, MBC contents under elevated CO₂ were higher than the corresponding values under ambient CO₂ (Fig. 75a). Higher values of MBC in soil were observed at flowering stage under both ambient and elevated CO₂. Microbial biomass carbon content in soil at flowering under ambient CO₂ was lower than the value recorded even at tillering under elevated CO₂.

The MBC contents in soil decreased with depth of soil under ambient and elevated CO₂ (Fig. 75b). Highest value of MBC was recorded in 0-5 cm soil layer in FACE field and then decreased significantly with depth. The MBC content in upper 0-5 cm soil layer in ambient field was lower than that in 5-10 cm soil layer in FACE field. The positive effect of elevation of atmospheric CO₂ was visible only in the upper three layers of soil. The soil at 15-20 cm layer did not show any significant gain in MBC content in response to higher CO₂ concentration in atmosphere.

b) Dissolved organic carbon (DOC)

The average values of DOC as individually affected by levels of CO₂, stages of growth and depth of soil are depicted in Figure 76.

Elevation of atmospheric CO₂ from 372 to 600 $\mu\text{mol mol}^{-1}$ caused an increase in DOC by 15.35 per cent (Fig. 76a).

Regarding the stages of crop growth, like pot culture experiment, field soil also showed maximum DOC content (130 mg kg^{-1}) at tillering and subsequently its value decreased significantly towards maturity (95.9 mg kg^{-1}) (Fig. 76b). The difference between DOC values at flowering and grain filling was not statistically significant yet, a significant increase in its value was observed between flowering and maturity stages. At tillering, absence of the secondary cell wall might probably have caused more leakage and exudation of carbonaceous substances from root cells thus raising the DOC content in soil.

Dissolved organic carbon content decreased with increase in soil depth (Fig. 76c). But its values in 0-5 and 5-10 cm soil layers were at statistically par. Dissolved organic carbon corresponding to the low molecular weight carbonaceous substances mainly is released as root exudates. As depth of

Fig. 76. Dissolved organic carbon (DOC, mg kg^{-1}) in soil during rice growth under FACE as influenced by the main effects of:

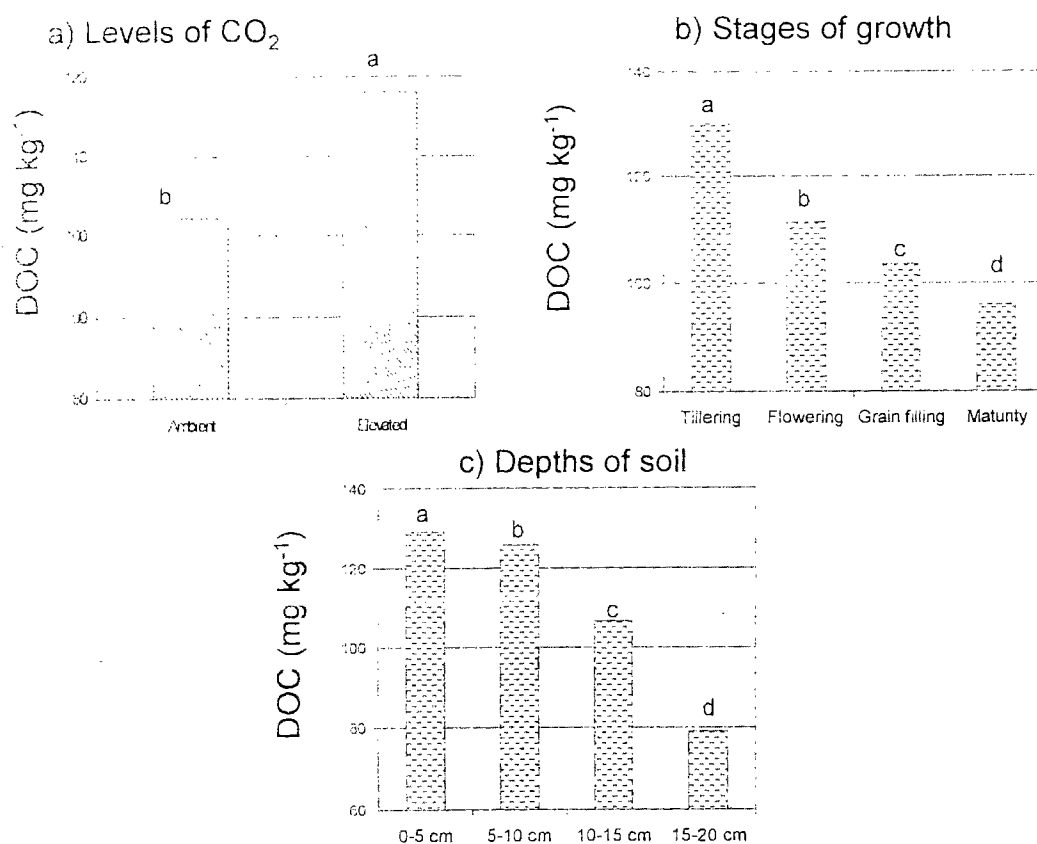
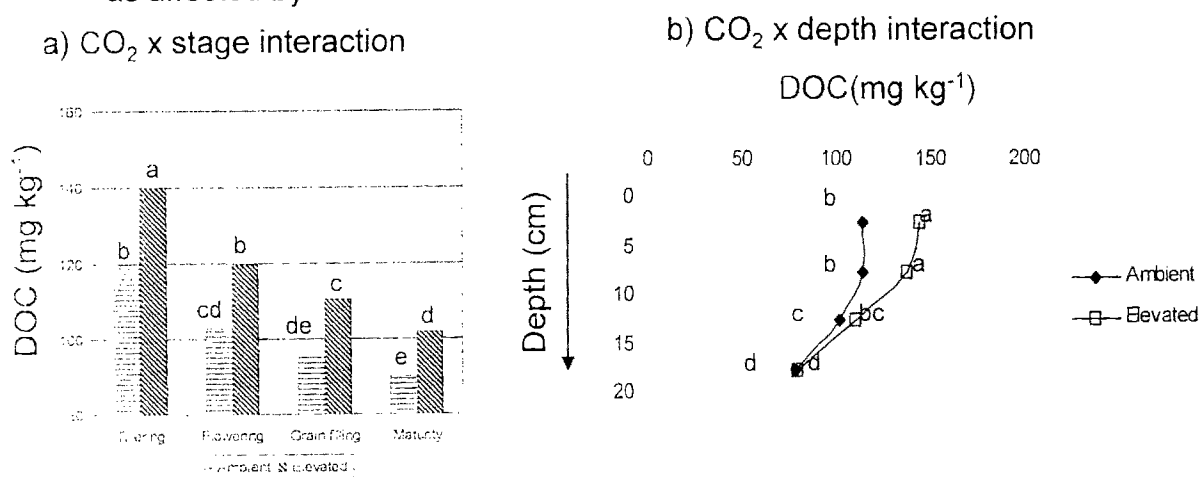


Fig. 77. Dissolved organic carbon (DOC, mg kg^{-1}) in soil during rice growth under FACE as affected by :



The differences between values with any common alphabet in figures are not statistically significant and vice versa

soil sampling increases, the root activity in terms of exudations diminishes. This might drop off DOC content in soil.

The two-way interaction between levels of CO₂ and stages of growth was also significant and the values are presented in Figure 77. Dissolved organic carbon contents in both elevated and ambient fields followed exactly the same trends with age of the crop, as described in the main effect of the growth stages (Fig. 77a). The value of DOC in soil at maturity stage under elevated CO₂ was on par with the corresponding value under ambient CO₂ concentration. At the other three stages, significant positive effect of elevation of atmospheric CO₂ concentration was observed with respect to DOC contents in soil.

The interaction between levels of CO₂ and depth of soil was also significant and the trends are shown in Figure 77b. The positive effect of higher CO₂ was observed only in the upper two layers of soil. In the lower two layers of soil the Duncan's letters were same in FACE and ambient fields. This reiterated the absence of the influence of elevation of atmospheric CO₂ concentration at lower soil depths.

c) Carbohydrate carbon (CHC)

Carbohydrate carbon, the impression of the structural carbohydrates of plant cells as effected by CO₂ levels, physiological stages of rice and depth of soil are depicted in Figure 78.

Elevation of CO₂ concentration in atmosphere increased the average CHC contents of soil by 8.04 per cent (Fig 78a). Like pot culture experiment, field soil also exhibited a significant increase in CHC content as the crop progressed from tillering to maturity (Fig. 78b).

There was a decrease in CHC content with increase in soil depth (Fig. 78c). The CHC content decreased from 2536 mg kg⁻¹ in upper 0-5 cm soil layer to 839.7 mg kg⁻¹ in lowest 15-20 cm layer, *i.e.*, the CHC content decreased to one third of its value, from 0-5 cm through 15-20 cm (Fig. 78c).

The interaction between levels of CO₂ and stages of rice growth had significant effect on CHC content in rice rhizosphere soil with higher values under elevated CO₂ at all stages of growth (Fig. 79a). Highest CHC (2193 mg kg⁻¹) was observed at maturity stage of rice growth in FACE soil. This was

Fig. 78. Carbohydrate carbon (CHC, mg kg^{-1}) in soil during rice growth under FACE as influenced by the main effects of:

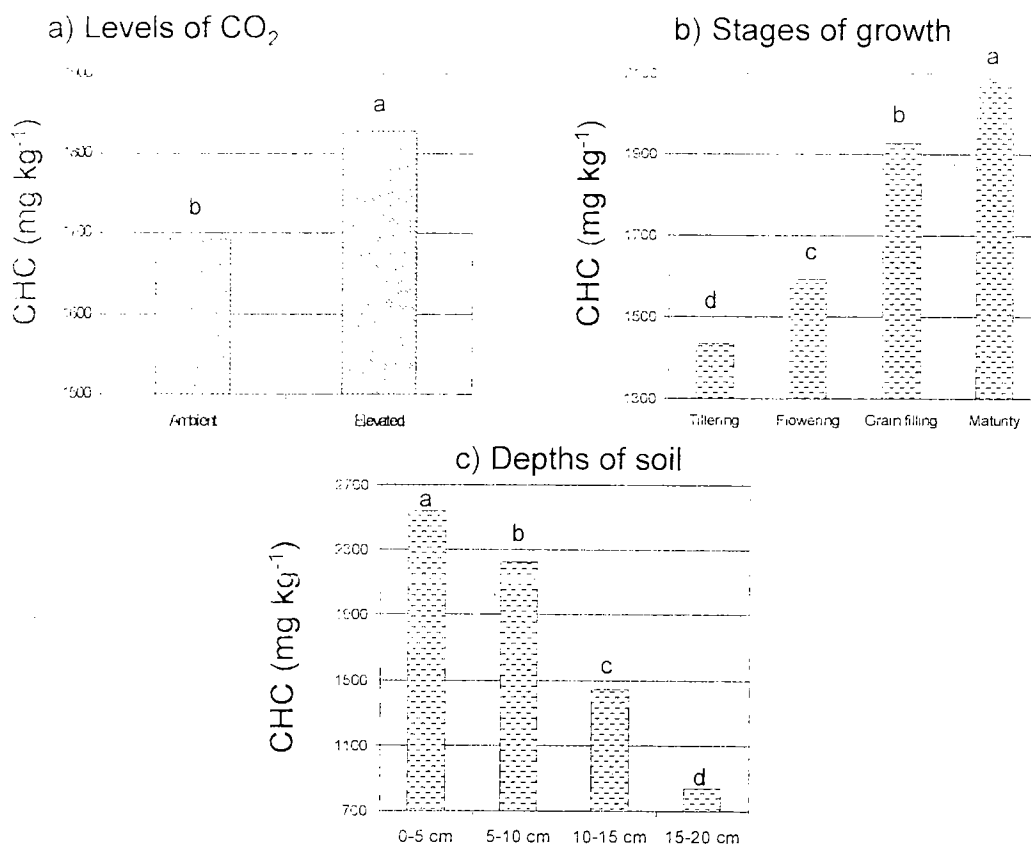
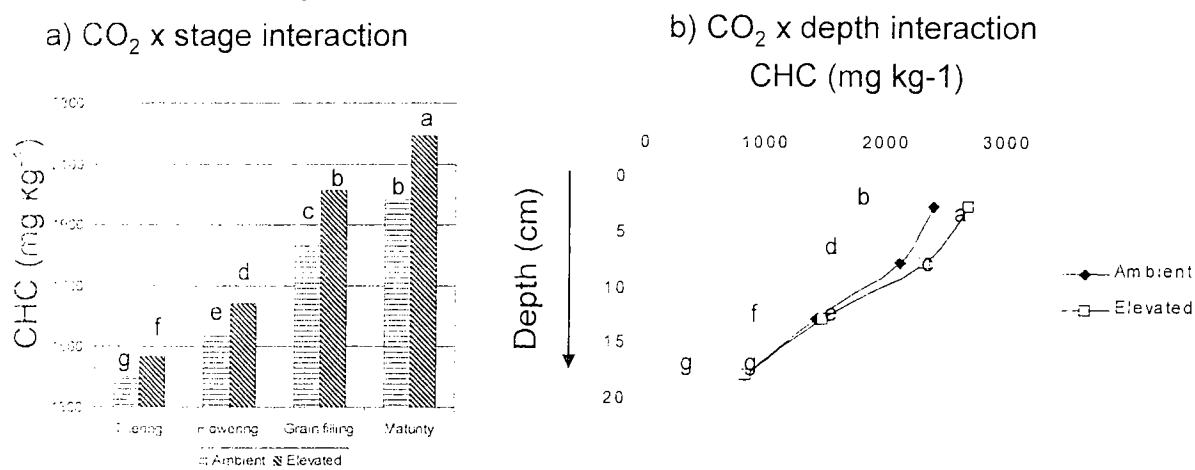


Fig. 79. Carbohydrate carbon (CHC, mg kg^{-1}) in soil during rice growth under FACE as affected by :



The differences between values with any common alphabet in figures are not statistically significant and vice versa

followed by that at grain filling stage in FACE field. The CHC content in soil at maturity under ambient CO₂ was lower than the value recorded even at grain filling stage under elevated CO₂.

The positive effect of elevation of atmospheric CO₂ concentration on CHC content in soil was visible in upper three layers studied (Fig. 79b). In the lower 15-20 cm soil layer, CHC contents were at par under both levels of CO₂.

The three-way interaction was also significant in case of CHC contents in soil (Table 43). Highest value of CHC was observed in 0-5 cm soil layer at maturity stage of rice under elevated atmospheric CO₂ concentration. The values of CHC ranged between 831.6 and 3440 mg kg⁻¹. At all stages of crop growth CHC contents in different soil layers in FACE field were higher over the corresponding values in ambient field.

d) Labile carbon (LBC)

The average LBC content in rice rhizosphere soil as influenced by the levels of CO₂, stages of growth and depth of soil are depicted in Figure 80.

The elevation of atmospheric CO₂ increased LBC content in rice rhizosphere soil by 7.43 per cent as the value increased from 1117 to 1200 mg kg⁻¹ (Fig. 80a).

Labile carbon is a relatively resistant (than the other three pools discussed) yet, soluble and easily oxidisable fraction of soil carbon. There was an increase in LBC content in soil with age of the crop (Fig. 80b). The highest value of LBC was recorded at maturity stage (1347 mg kg⁻¹) and the lowest at tillering (949.1 mg kg⁻¹). The higher values of LBC content in soil at maturity could possibly be explained by the lysis and degradation of the root mass.

There was a decrease in average LBC content down the soil profile (Fig. 80c). The lower soil layers had significantly lesser amounts of LBC compared to the upper layers.

The interactions between CO₂ and depth of soil as well as CO₂ and stages were significant during rice growth and the trends are shown in Figure 81. At all stages of crop growth, LBC contents in soil were higher in FACE field than the corresponding values in ambient field (Fig. 81a). Highest value of LBC in soil was observed at maturity in FACE field. The LBC content in

Table 43. Carbohydrate carbon (CHC, mg kg⁻¹) in soil samples collected from different depths at various physiological stages of rice grown under FACE

Depth (cm)	Physiological stages			
	Tillering	Flowering	Grain filling	Maturity
Ambient				
0-5	1789 ^{ijkl}	2148 ^h	2648 ^d	2988 ^b
5-10	1756 ^{kl}	1856 ^{jk}	2379 ^{fg}	2493 ^{ef}
10-15	1226 ^k	1342 ^{qr}	1486 ^{op}	1611 ^{mn}
15-20	833.2 ^s	832.7 ^s	843.4 ^s	842.2 ^s
Elevated				
0-5	1907 ^{ij}	2324 ^g	3044 ^b	3440 ^a
5-10	1873 ^{ijk}	1987 ⁱ	2616 ^{de}	2804 ^c
10-15	1262 ^r	1408 ^{pq}	1540 ^{no}	1682 ^{lm}
15-20	831.6 ^s	839.0 ^s	850.5 ^s	844.7 ^s

The differences between values with any common alphabet in superscript in table are not statistically significant and *vice versa*

Fig. 80. Labile carbon (LBC, mg kg^{-1}) in soil during rice growth under FACE as influenced by the main effects of:

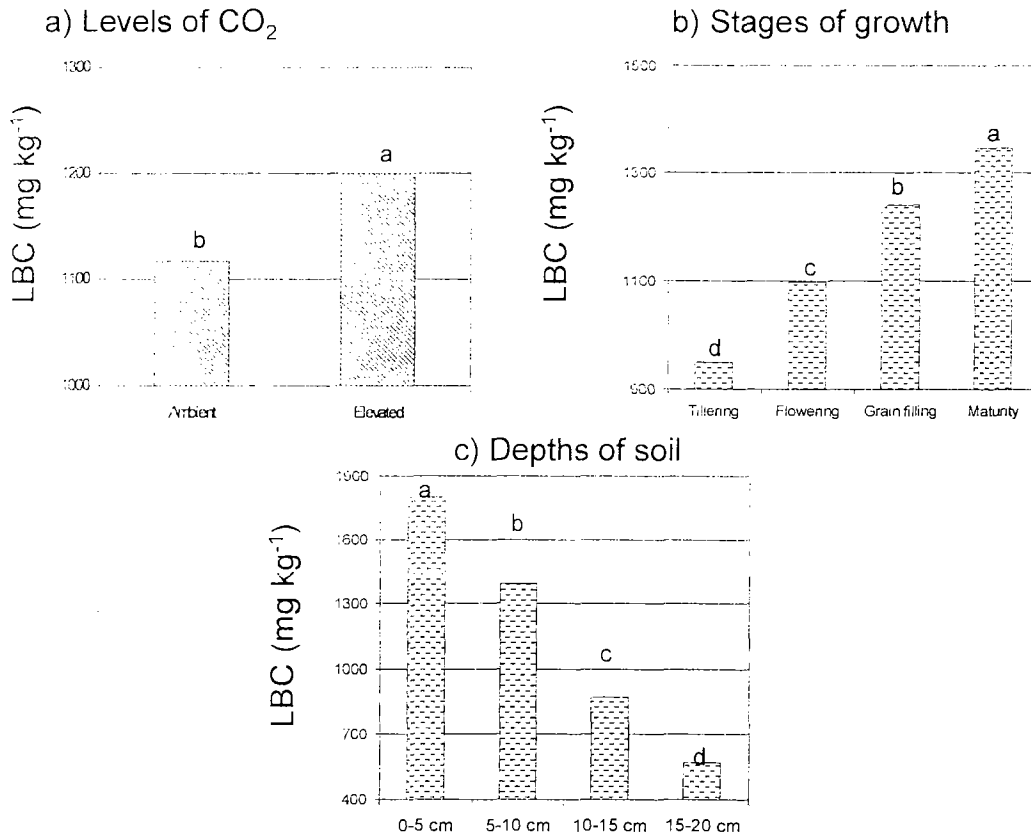
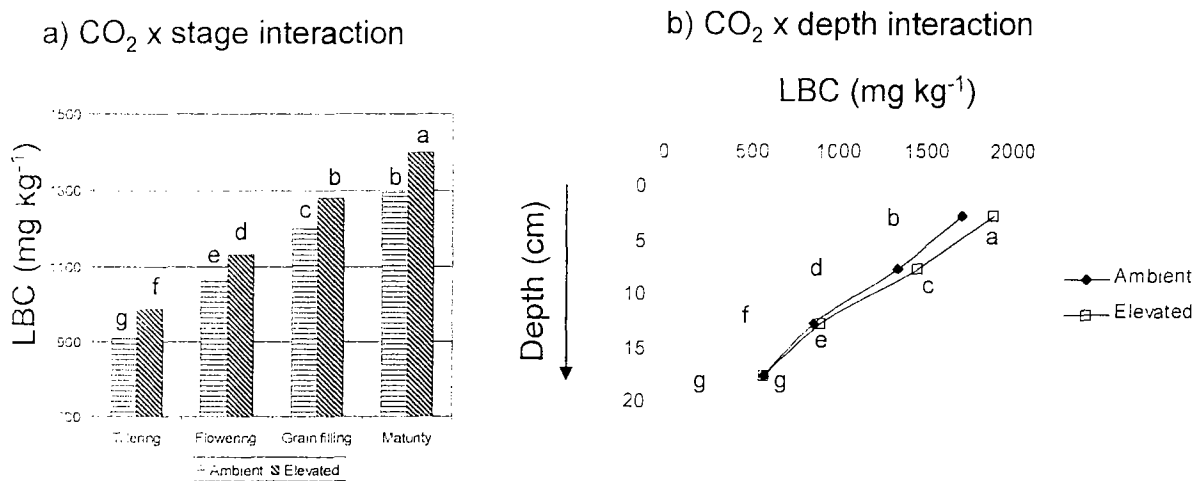


Fig. 81. Labile carbon (LBC, mg kg^{-1}) in soil during rice growth under FACE as affected by :



The differences between values with any common alphabet in figures are not statistically significant and *vice versa*

ambient field at maturity was on par with the value at grain filling stage in FACE field.

At all soil depths, LBC contents were higher in FACE when compared to the corresponding values in ambient field (Fig. 81b). The positive effect of elevation of atmospheric CO₂ concentration on LBC content was observed in the upper three layers of soil. In the 15- 20 cm soil layer the LBC values were similar in FACE and ambient fields. This also reinforced the absence of the effect of higher CO₂ concentration on active carbon pools in soil at lower depths

e) Total soil carbon (TSC)

The values pertaining to TSC content in soil as functions of levels of CO₂, physiological stages and depth of soil are presented in Figure 82.

The elevation of atmospheric CO₂ concentration in field had increased the total carbon content in soil from 9.03 to 9.23 g kg⁻¹ (Fig. 82a). This increase in TSC content implied the significance of long-term effect of higher atmospheric CO₂ on soil. The FACE facility has been continuously used by scientists for research purpose for the past seven years (Uprety *et al.*, 2003). This long-term exposure of soil to CO₂ might have resulted in an increase in carbon content of soil. However stages of crop growth did not significantly influence the TSC content. There was a rapid decrease in TSC content from surface to subsurface soil depths (Fig. 82b).

The interaction between CO₂ levels and stages of crop growth was not significant but, that between CO₂ levels and depth of soil was significant and the values are depicted in Figure 83. It is very interesting to note that the effect of elevation of atmospheric CO₂ concentration was observed only in the upper 0-5 cm soil layer. In this upper soil layer, the TSC content was significantly higher under elevated CO₂ than under ambient CO₂. The TSC values in the lower soil layers in ambient and FACE fields were at par.

Three-way interaction among CO₂ levels, stages of rice growth and depth of soil sampling was not significant.

Fig. 82. Total soil carbon (TSC, g kg⁻¹) in soil during rice growth under FACE as influenced by the main effects of:

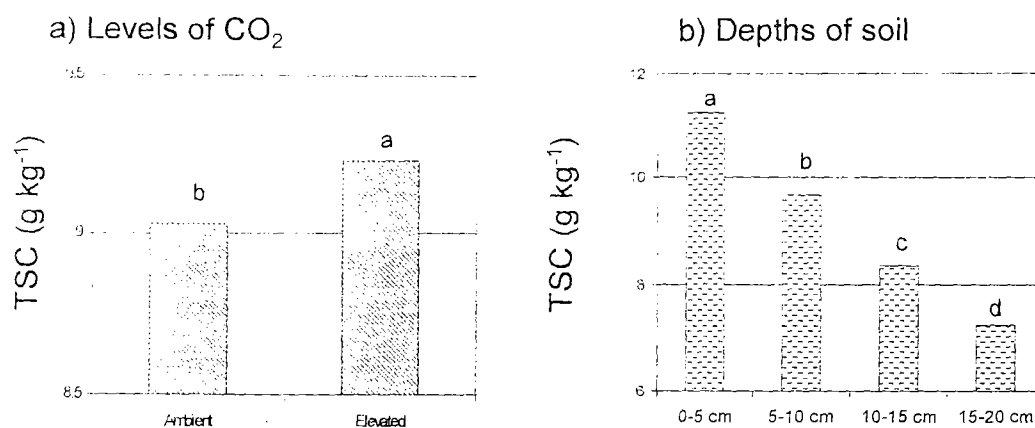
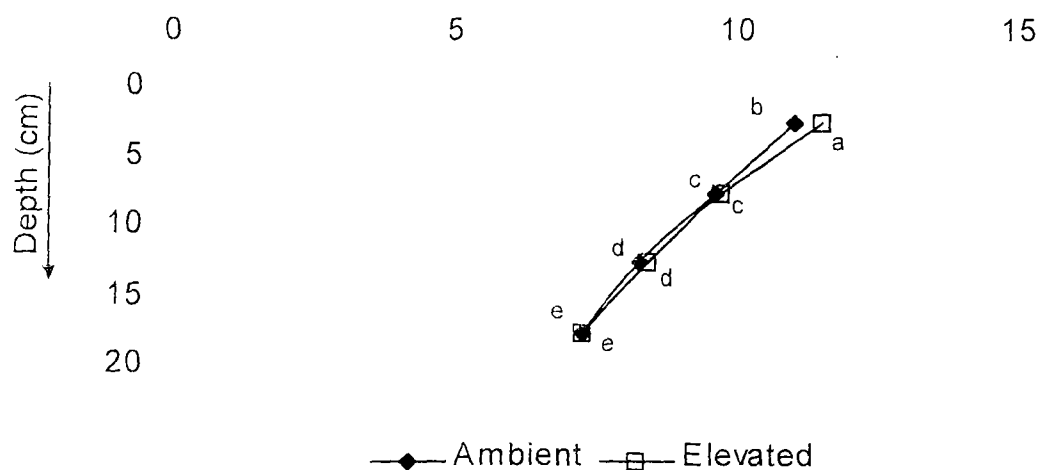


Fig. 83. Total soil carbon (TSC, g kg⁻¹) in soil during rice growth under FACE as affected by the interaction between CO₂ level and depths of soil



The differences between values with any common alphabet in figures are not statistically significant and *vice versa*

4.2.2 Wheat crop

a) Microbial biomass carbon

The data pertaining to average MBC content in soil during wheat crop as affected by the levels of CO₂ stages of growth and depth of soil are given in the Figure 84.

As a result of elevation of atmospheric CO₂, an increase in MBC content by 17.3 per cent was observed in FACE soil when wheat followed the rice in sequence (Fig. 84a).

Microbial biomass carbon content in soil was found to be maximum at anthesis stage. Later, as the crop progressed to maturity an abrupt decrease in MBC content was recorded (Fig. 84b).

Generally, as the depth of soil increased from 0 to 20 cm, there was a decline in MBC values (Fig. 84c). Nevertheless, MBC contents in 0-5 and 5-10 cm soil layers were at par. As a whole, the average MBC content decreased from 422.8 to 284.6 mg kg⁻¹ from surface through 20 cm soil layer.

The mutual interactions of the levels of CO₂ with stages of growth and with depth of soil were also significant and values are presented in Figure 85. At all stages of wheat growth, MBC contents under elevated CO₂ were higher than the corresponding values under ambient CO₂ (Fig. 85a). Highest value of MBC in wheat rhizosphere soil was observed at anthesis stage under elevated CO₂. This was followed by MBC content at CRI stage under elevated CO₂ and this value was on par with the MBC content in ambient field at anthesis stage of wheat growth.

MBC contents in soil decreased with depth of soil under ambient and elevated CO₂ concentrations in atmosphere (Fig. 85b). Highest value of MBC was observed at 0-10 cm soil layer in FACE field and then decreased significantly with depth. The MBC contents in upper 0-5 and 5-10 cm soil layers in ambient field were also at par. The positive effect of elevation of atmospheric CO₂ was observed only in the upper three soil layers. Microbial biomass carbon in 15-20 cm soil layer did not exhibit any significant change in response to the higher CO₂ concentration in atmosphere.

Fig. 84. Microbial biomass carbon (MBC mg kg^{-1}) in soil during wheat growth under FACE as influenced by the main effects of:

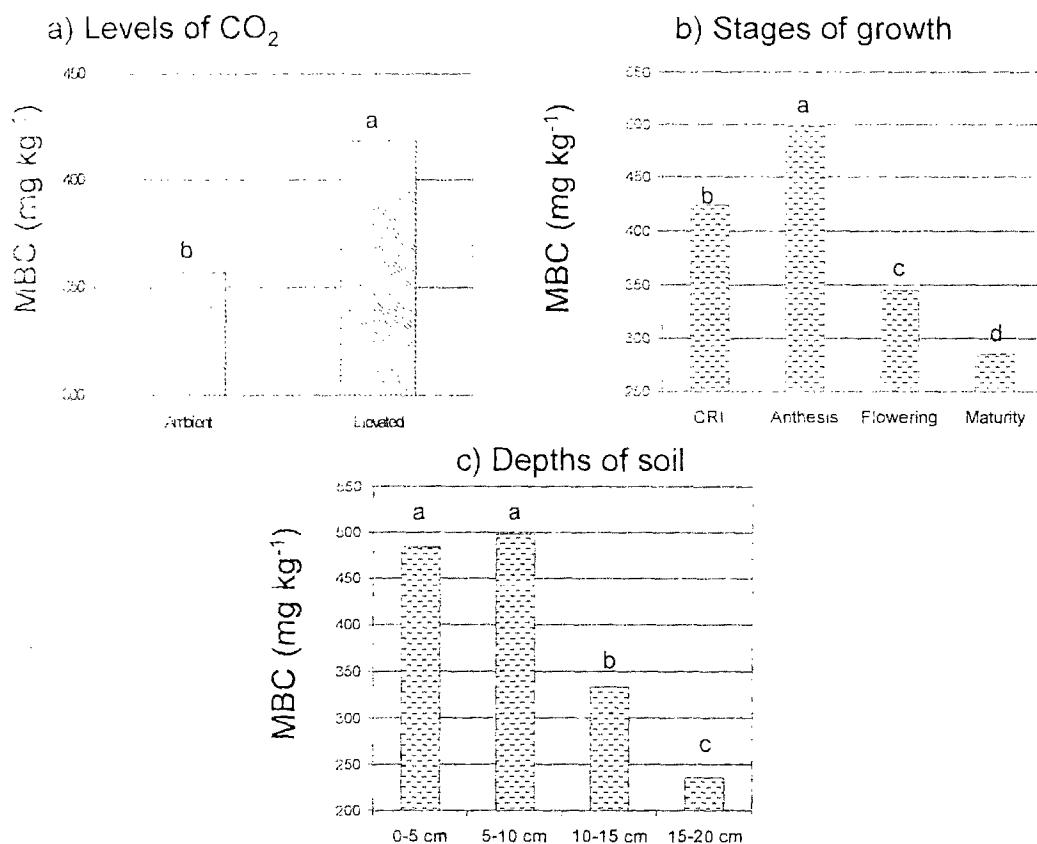
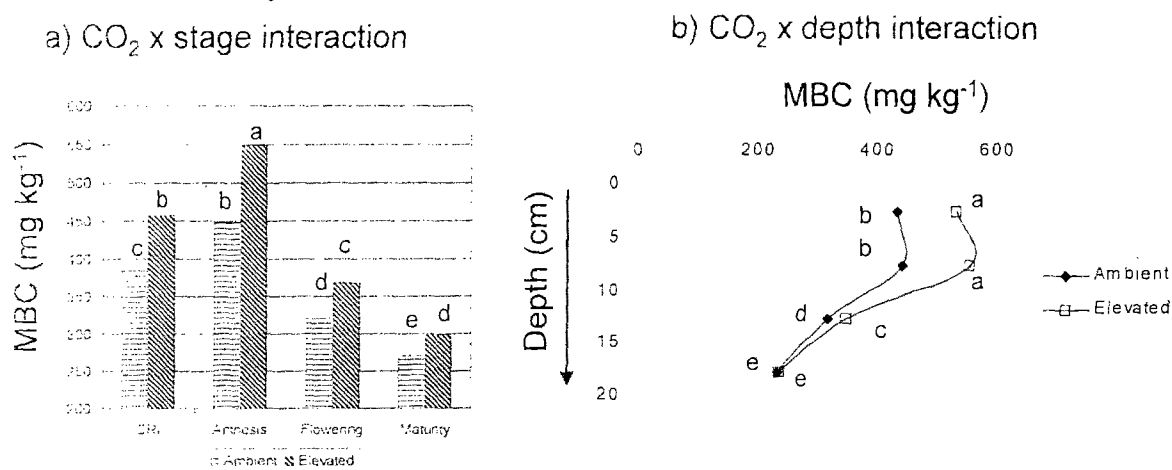


Fig. 85. Microbial biomass carbon (MBC, mg kg^{-1}) in soil during wheat growth under FACE as affected by :



The differences between values with any common alphabet in figures are not statistically significant and *vice versa*
 CRI : Crown root initiation

b) Dissolved organic carbon (DOC)

The average values of DOC as individually influenced by levels of CO₂, stages of crop growth and depth of soil are depicted in Figure 86. Elevation of atmospheric CO₂ from 372 to 600 $\mu\text{mol mol}^{-1}$ has caused an increase in DOC by more than seventeen per cent; i.e., the absolute value increased from 102.3 mg kg⁻¹ under ambient to 120.0 mg kg⁻¹ under elevated CO₂ (Fig. 86a).

Regarding the stages of crop growth, as in pot culture experiment, DOC was maximum at CRI and got decreased significantly as the crop approached maturity (Fig. 86b). A similar trend was observed in wheat also.

In general, DOC content decreased with increase in depth of soil. But the average DOC content in 5-10 cm soil layer was significantly higher to that in upper 0-5 cm layer (Fig. 86c). Dissolved organic carbon corresponds to the low molecular weight carbonaceous substances mainly coming from the root exudates. This fraction is labile and is highly degradable. As the upper soil layer is exposed to the atmosphere a slightly smaller value of DOC is expected. However, as the soil depth increased beyond 10 cm a decrease in DOC content was observed which could probably be attributed to the lower root activity and exudations.

The two-way interaction between CO₂ levels and stages of growth was also significant and the values are presented in Figure 87. DOC values in both elevated and ambient fields followed the same trends with physiological stages of wheat growth, as described in the main effect (Fig. 87a). Yet, in FACE field anthesis and grain filling stages did not differ significantly with respect to DOC contents in soil. At all stages of crop growth, a significantly positive effect of elevation of atmospheric CO₂ concentration was observed with respect to DOC content in soil. The DOC content in soil was highest at CRI stage in FACE field. This was followed by the value at anthesis in FACE soil, which was on par with the DOC content at CRI stage in ambient field. The CRI stage in ambient field and the grain filling stage in FACE field during wheat growth did not differ significantly. Similarly, it is clear from the figure that there is no significant difference between the grain filling stage in FACE and maturity stage in ambient fields.

Fig. 86. Dissolved organic carbon (DOC, mg kg^{-1}) in soil during wheat growth under FACE as influenced by the main effects of:

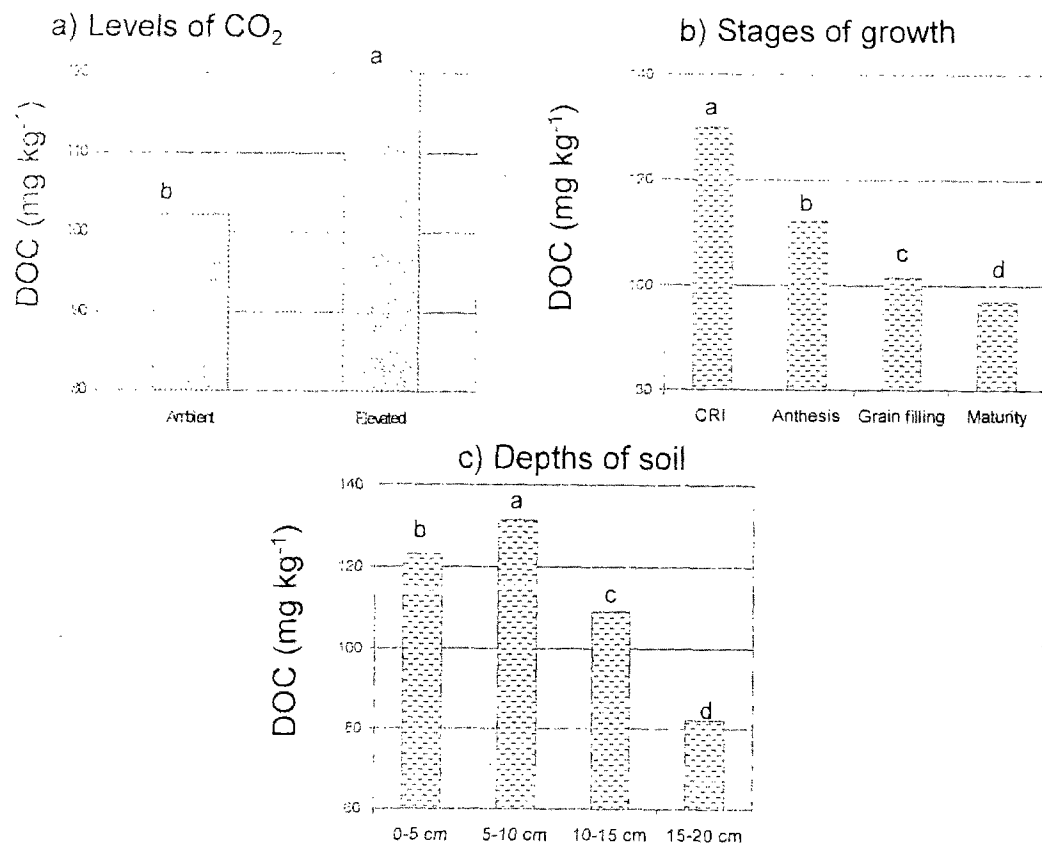
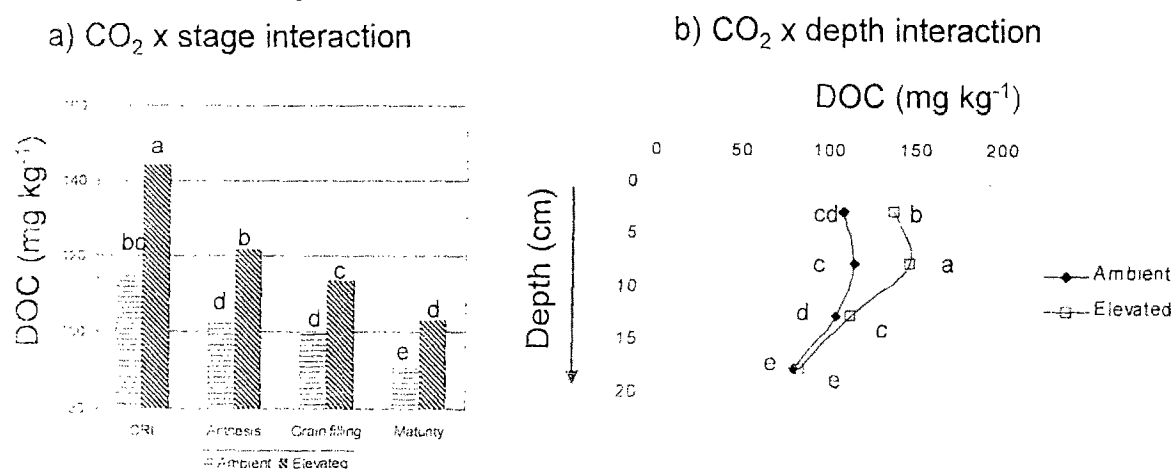


Fig. 87. Dissolved organic carbon (DOC, mg kg^{-1}) in soil during wheat growth under FACE as affected by :



The differences between values with any common alphabet in figures are not statistically significant and *vice versa*

CRI : Crown root initiation

The interaction between levels of CO₂ and depth of soil was also significant and the trends are depicted in Figure 87b. The positive effect of higher CO₂ was observed in the upper three soil layers. In the lower soil layer, the DOC content in FACE did not differ from that in ambient field. This reiterated the absence of the influence of elevation of atmospheric CO₂ concentration on DOC content in lower soil layers.

c) Carbohydrate carbon (CHC)

Carbohydrate carbon measured during wheat growth as affected by levels of CO₂, stages of growth and depth of soil are depicted in Figure 88.

Elevation of CO₂ concentration in atmosphere increased the average CHC content of soil by 8.9 per cent (Fig. 88a). As observed in pot culture study, CHC content in field also increased significantly from CRI to maturity (Fig. 88b).

The CHC content in soil decreased with increase in soil depth (Fig. 88c). Its value decreased from 2496 mg kg⁻¹ in upper 0-5 cm soil layer to 897.3 mg kg⁻¹ in the 15-20 cm layer. But the upper 0-5 and 5-10 cm soil layers did not differ significantly with respect to this carbon pool.

The interaction between levels of CO₂ and physiological stages of wheat was significant in wheat soil with higher values of CHC under elevated CO₂ at all the stages of growth (Fig. 89a). Highest CHC (2333 mg kg⁻¹) content was observed at maturity in FACE soil. This was followed by the CHC content at grain filling in FACE soil, which was found to be on par with value observed at the maturity in ambient field.

In ambient field, CHC content did not change significantly from 0-5 to 5-10 cm soil layer (Fig. 89b). But beyond 10 cm soil layer, CHC decreased rapidly up to 15-20 cm down the surface. The positive effect of elevation of atmospheric CO₂ concentration on CHC contents in soil was visible in upper three layers studied. The lower 15-20 cm layer did not exhibit any significant influence of the higher level of CO₂.

The three-way interaction was also significant and the values with Duncan superscripts are presented in Table 44. Carbohydrate carbon content was observed to be maximum at maturity in 0-5 cm soil layer under elevated atmospheric CO₂ concentration. The values ranged between 869.1 and 3230

Fig. 88. Carbohydrate carbon (CHC, mg kg^{-1}) in soil during wheat growth under FACE as influenced by the main effects of:

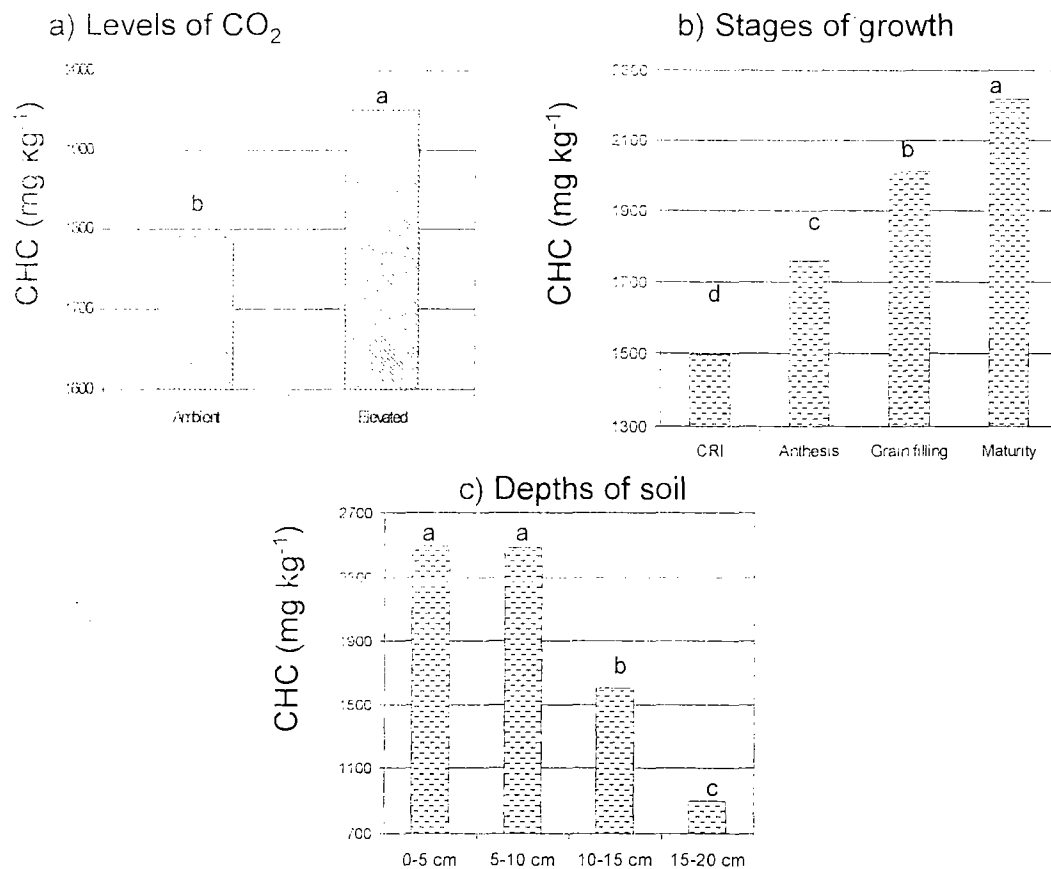
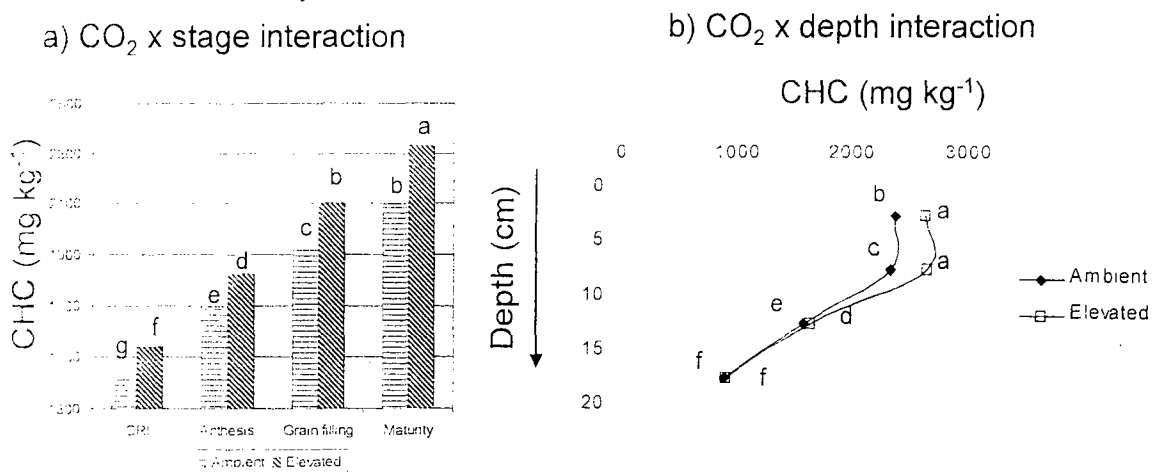


Fig. 89. Carbohydrate carbon (CHC, mg kg^{-1}) in soil during wheat growth under FACE as affected by :



The differences between values with any common alphabet in figures are not statistically significant and *vice versa*

CRI : Crown root initiation

mg kg⁻¹. At all stages of crop growth, CHC contents in different soil layers in FACE field were higher to the corresponding values in ambient field with certain exceptions in the lowest soil layer studied.

d) Labile carbon (LBC)

Labile carbon contents in wheat rhizosphere soil as independently influenced by levels of CO₂, stages of growth and depth of soil are depicted in Figure 90. The elevation of atmospheric CO₂ increased average LBC content in wheat rhizosphere soil by 8.38 per cent as the value increased from 1170 under ambient to 1268 mg kg⁻¹ (Fig. 90a).

With advancement of age, LBC content in soil increased during wheat growth (Fig. 90b). The highest value was observed at maturity stage and the lowest at CRI. All the stages of wheat growth differed significantly with respect to this carbon pool. The higher value of LBC content in soil at maturity can be ascribed to the lysis and degradation of the root mass.

in general, LBC content decreased with increase in soil depth when wheat was grown in field (Fig. 90c). The surface soil layers had significantly higher amount of LBC than the lower layers. The upper two layers of soil did not exhibit any significant difference with respect to the average LBC content.

The interaction between CO₂ and depth of soil as well as CO₂ and stages of crop growth was significant during wheat growth and the trends are shown in Figure 91.

In both ambient and FACE fields, the upper two soil layers did not differ significantly with respect to LBC content in soil (Fig. 91b). At all soil depths, the LBC content was higher in FACE than the corresponding values in ambient field. The positive effect of elevation of atmospheric CO₂ concentration on LBC content was observed in the upper two layers of soil. The lower soil layers did not exhibit any effect of elevation of atmospheric CO₂ as the LBC values in ambient and FACE fields did not differ significantly.

e) Total soil carbon

The values pertaining to average TSC content as functions of levels of CO₂, stages of growth and depth of soil are presented in Figure 92. The elevation of atmospheric CO₂ concentration in field had increased the total carbon content from 9.23 to 9.59 g kg⁻¹. This increase in TSC reiterated the

Fig. 90. Labile carbon (LBC, mg kg^{-1}) in soil during wheat growth under FACE as influenced by the main effects of:

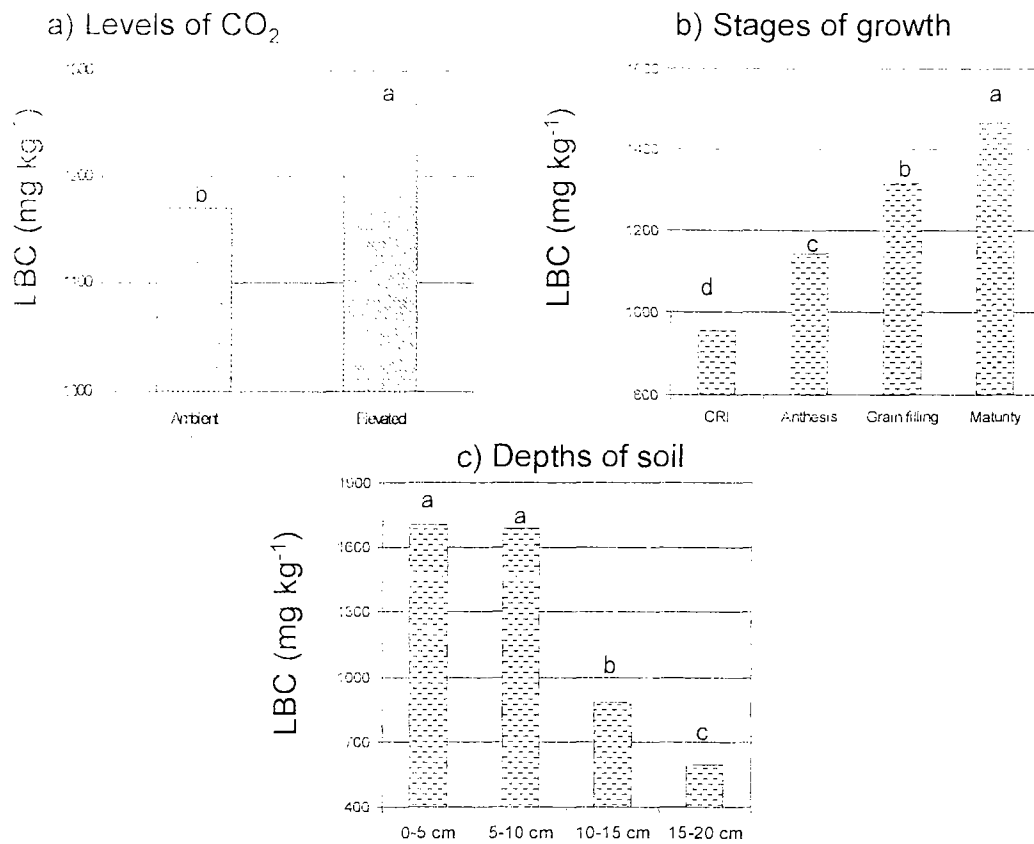
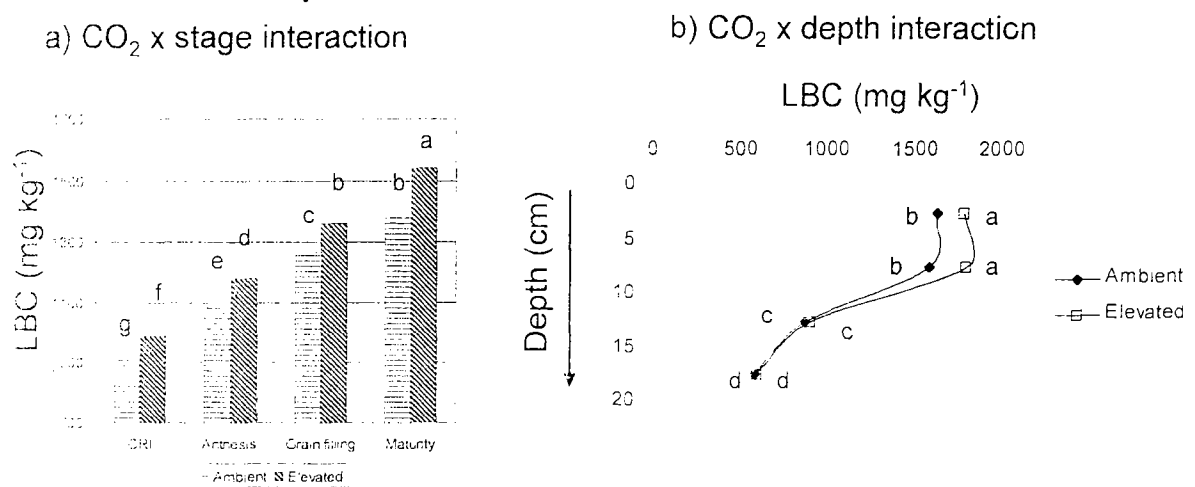


Fig. 91. Labile carbon (LBC, mg kg^{-1}) in soil during wheat growth under FACE as affected by :



The differences between values with any common alphabet in figures are not statistically significant and *vice versa*

CRI : Crown root initiation

long-term effect of higher CO₂ on carbon sequestration. Stages of crop growth did not have any significant effect on TSC values. Yet, the value increased slightly with age of crop (Fig. 92b).

There was a gradual decrease in TSC content with soil depth (Fig. 92c). But the TSC contents in the upper two layers were at par.

The interaction between CO₂ levels and stages of crop growth was not significant but, that between CO₂ levels and depth of soil was significant and the values are depicted in Figure 93. It is very interesting to note that the effect of elevation of atmospheric CO₂ concentration was observed in two upper soil layers. Within a depth of 10 cm, the TSC content was higher under elevated CO₂. Thus positive effect of elevated CO₂ existed in the upper two soil layers.

Three-way interaction between CO₂ levels, stages of growth and depth of soil was not significant.

4.2.3 Gains in active carbon pools

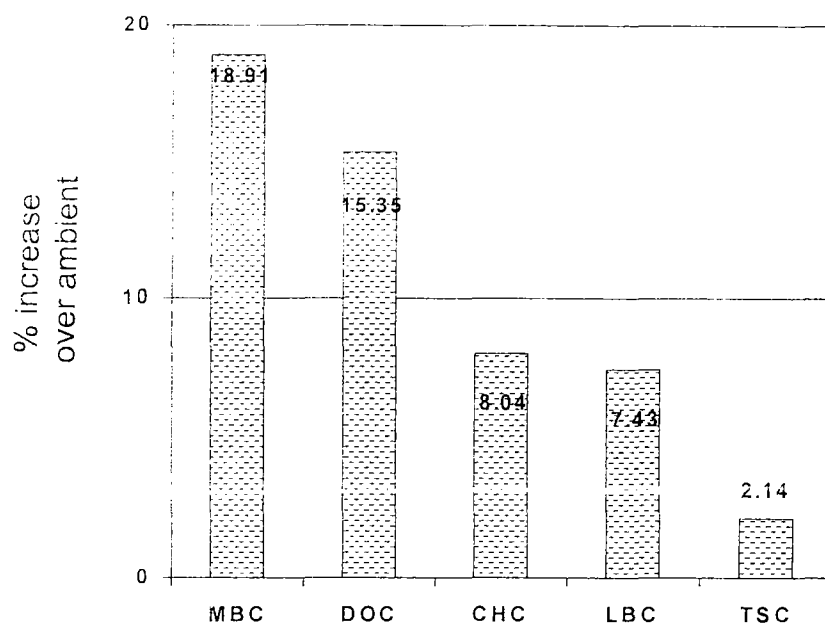
Elevation of atmospheric CO₂ concentration had increased all active carbon pools in soil under FACE. An interesting observation is the increase in TSC content as a result of higher CO₂. The results from pot culture experiment in OTCs as well as field experiment in FACE recorded gain in active pools of carbon while the increase in TSC was observed in FACE only. Moreover, two experiments differed with respect to absolute values of the per cent gains in the carbon pools with increase in atmospheric CO₂ concentration. Here also rice and wheat differed with respect to the mostly affected active carbon pool by the elevation of CO₂ concentration in their microclimates.

Average gains in the active carbon pools and TSC due to elevation of atmospheric CO₂ concentration in rice and wheat crops are presented in Figure 94. Among the four pools studied MBC content in rhizosphere soil of rice had maximum benefit recording 18.91 per cent increase over that in ambient treatment. This was followed by the gain in DOC content, which amounted to 15.35 per cent in FACE field.

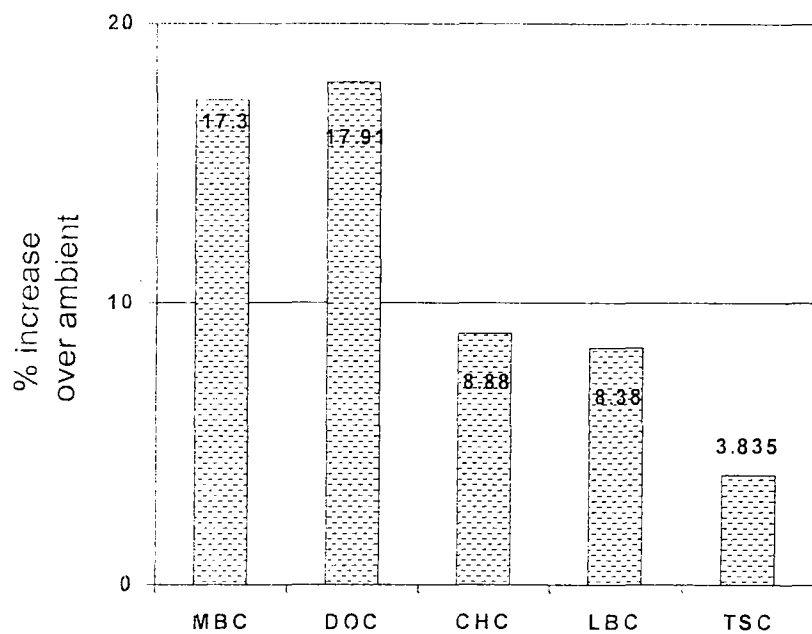
In wheat, maximum increase was recorded in DOC content in response to the increased CO₂ recording a 17.91 per cent increase. The MBC content

Fig. 94. Per cent increase in different carbon fractions in FACE field with test crops as influenced by elevation of CO₂

Rice



Wheat



in wheat soil was increased by 17.3 per cent and this was next only to DOC. These two carbon pools represent most labile fractions (among the four pools studied) and are very sensitive to the changes in management or agronomic practices. Carbohydrate carbon content experienced a gain of 8.04 per cent in rice field under elevated CO_2 while in wheat field an increase of 8.88 per cent was recorded. The LBC content in soil increased by 7.55 and 8.38 per cent in rice and wheat fields, respectively.

The per cent increase in these active carbon pools in soil collected from different depths on exposure to elevated CO_2 also declined as depth of sampling increased. In rice field, the average gain in MBC in 0-5 cm soil layer was by 30.9 per cent and this got reduced to merely 1.5 per cent in the lowest layer studied (Table 45). A similar reduction was noticed in other carbon pools too (Table 46, 47 and 48). Thus in rice, the per cent response in active carbon pools to elevation of atmospheric CO_2 concentration was highest in 0-5 cm soil layer. But in case of wheat, it was highest in 5-10 cm soil layer, excepting DOC where the two upper layers did not differ with respect to the per cent response (Tables 49-52). The DOC content in 0-5 cm soil layer was increased by 28 per cent while that in 5-10 cm layer increased by 27.5 per cent. Nevertheless, relative advantage of elevation in CO_2 is restricted to the upper soil layers signifying the importance of rhizosphere effect and root exudations.

4.2.4 Relative build up of active carbon pools

The relative build up of the active carbon pools; MBC, DOC, CHC and LBC in the rhizosphere soils of both crops under ambient and elevated atmospheric CO_2 conditions are depicted in Figures 95 and 96.

The figures represent the build up of the active carbon pools in rice and wheat rhizospheres when the average values of the pools (averaged over all growth stages) were expressed in relation to their initial values. The relative accumulation of all active carbon pools was higher under elevated atmospheric CO_2 concentration in rhizospheres of both the crops. The relative build up was found to be more in MBC and DOC as their gain was greater than CHC and LBC.

Table 45. Per cent changes in microbial biomass carbon (MBC) in soil at different depths at various stages of rice growth as affected by the elevation of CO₂ under FACE

Depth (cm)	Tillering	Flowering	Grain Filling	Maturity	Mean
0-5	34.56	32.32	30.71	26.04	30.91
5-10	26.84	27.33	17.62	15.92	21.93
10-15	8.444	11.69	6.477	3.663	7.568
15-20	1.734	1.921	0.240	2.282	1.545
Mean	17.89	18.31	13.76	11.98	

Table 46. Per cent changes in dissolved organic carbon (DOC) in soil at different depths at various stages of rice growth as affected by the elevation of CO₂ under FACE

Depth (cm)	Tillering	Flowering	Grain Filling	Maturity	Mean
0-5	27.82	32.30	23.71	21.42	26.31
5-10	24.16	18.07	20.72	19.79	20.68
10-15	8.389	10.05	7.476	6.520	8.109
15-20	-1.598	-0.013	2.185	2.300	0.719
Mean	14.69	15.10	13.52	12.51	

Table 47. Per cent changes in Carbohydrate carbon (CHC) in soil at different depths at various stages of rice growth as affected by the elevation of CO₂ under FACE

Depth (cm)	Tillering	Flowering	Grain Filling	Maturity	Mean
0-5	6.631	8.370	14.97	15.14	11.28
5-10	6.646	7.083	9.979	12.50	9.051
10-15	2.997	5.007	3.767	4.440	4.053
15-20	-0.198	0.848	0.903	0.238	0.448
Mean	4.019	5.327	7.405	8.079	

Table 48. Per cent changes in labile carbon (LBC) in soil at different depths at various stages of rice growth as affected by the elevation of CO₂ under FACE

Depth (cm)	Tillering	Flowering	Grain Filling	Maturity	Mean
0-5	12.35	8.725	9.356	11.70	10.53
5-10	12.43	8.346	8.208	6.343	8.831
10-15	2.489	3.209	3.291	9.567	4.639
15-20	-0.547	0.348	0.388	0.554	0.186
Mean	6.680	5.157	5.311	7.040	

Table 49. Per cent changes in microbial biomass carbon (MBC) in soil at different depths at various stages of wheat growth as affected by the elevation of CO₂ under FACE.

Depth (cm)	CRI	Anthesis	Grain Filling	Maturity	Mean
0-5	26.96	28.91	17.56	13.51	21.74
5-10	26.65	31.97	23.12	16.70	24.61
10-15	9.711	10.14	10.97	9.883	10.18
15-20	5.908	1.685	2.827	0.632	2.763
Mean	17.31	18.18	13.62	10.18	

Table 50. Per cent changes in dissolved organic carbon (DOC) in soil at different depths at various stages of wheat growth as affected by the elevation of CO₂ under FACE.

Depth (cm)	CRI	Anthesis	Grain Filling	Maturity	Mean
0-5	44.62	25.92	14.12	27.35	28.00
5-10	29.93	29.81	27.31	23.11	27.54
10-15	10.14	9.712	8.765	5.281	8.475
15-20	8.607	2.904	6.509	3.293	5.328
Mean	23.33	17.09	14.17	14.76	

CRI : Crown root initiation

Table 51. Per cent changes in Carbohydrate carbon (CHC) in soil at different depths at various stages of wheat growth as affected by the elevation of CO₂ under FACE

Depth (cm)	CRI	Anthesis	Grain Filling	Maturity	Mean
0-5	7.886	7.638	16.08	14.58	10.39
5-10	8.444	9.485	15.89	16.66	12.62
10-15	3.823	3.815	4.642	4.964	4.311
15-20	-0.684	2.325	1.503	1.431	1.144
Mean	5.193	6.607	7.780	8.889	

Table 52. Per cent changes in labile carbon (LBC) in soil at different depths at various stages of wheat growth as affected by the elevation of CO₂ under FACE

Depth (cm)	CRI	Anthesis	Grain Filling	Maturity	Mean
0-5	9.688	9.168	9.542	10.83	9.808
5-10	12.05	9.639	11.44	17.46	12.65
10-15	5.766	2.697	0.924	5.240	3.657
15-20	-1.391	4.651	-0.438	1.618	1.110
Mean	6.529	6.539	5.366	8.788	

CRI : Crown root initiation

Fig. 95. Relative increase (per cent) in different active carbon pools (averaged over all the crop growth stages) in FACE field during rice growth as influenced by elevation of CO₂

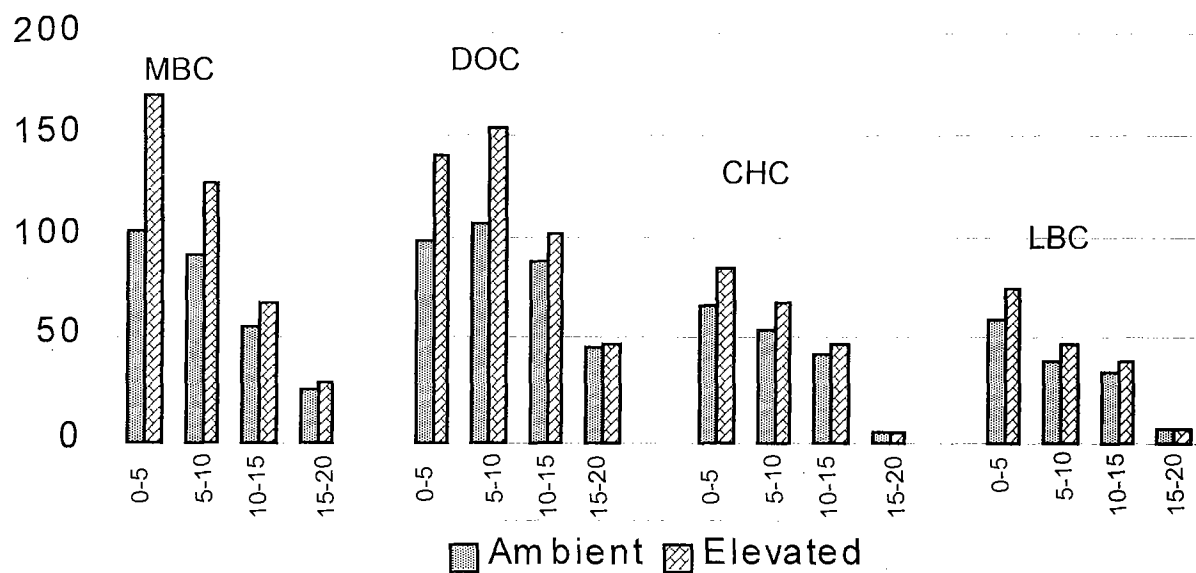
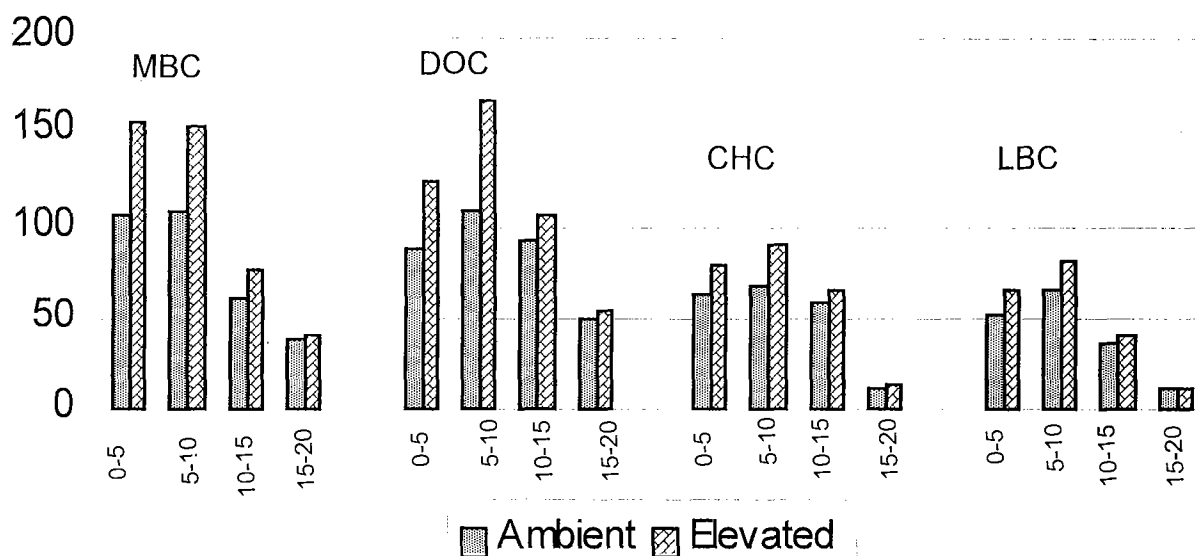


Fig. 95. Relative increase (per cent) in different active carbon pools (averaged over all the crop growth stages) in FACE field during wheat growth as influenced by elevation of CO₂



4.3 DECOMPOSITION STUDY

The results of study related to decomposition of rice and wheat residues grown both in ambient and elevated CO₂ conducted in phytotron chambers are discussed under the following headings and sub headings:

4.3.1 Decomposition kinetics of ambient (RA) and elevated (RE) CO₂-grown rice residues

4.3.1.1 Residue parameters

- a) Amount of the residues remaining in nylon bags
- b) Carbon content
- c) C:N ratio
- d) Kinetics of decomposition of the RA and RE

4.3.1.2 Soil parameters

- a) Total organic carbon
- b) Microbial biomass carbon
- c) Ammoniacal nitrogen
- d) Nitrate nitrogen

4.3.2 Decomposition kinetics of ambient (WA) and elevated (WE) CO₂-grown wheat residues

4.3.2.1 Residue parameters

- a) Amount of the residues remaining in nylon bags
- b) Carbon content
- c) C:N ratio
- d) Kinetics of decomposition of WA and WE

4.3.2.2 Soil parameters

- a) Total organic carbon
- b) Microbial biomass carbon
- c) Ammoniacal nitrogen
- d) Nitrate nitrogen

4.3.1 Decomposition kinetics of ambient (RA) and elevated CO₂ (RE)-grown rice residues

Ambient (RA) and elevated CO₂-grown (RE) rice residues were allowed to decompose for a period of 150 days in litterbags inserted into soil in pots. The results of the decomposition study are discussed here.

4.3.1.1 Residue parameters

a) Amount of residue remaining inside the nylon bags

The average (averaged over six replications) amount of ambient and elevated CO₂-grown rice residues remaining inside the litterbag at different times of sampling during decomposition are presented in Figure 97.

The ambient and elevated CO₂-grown rice residues got reduced to 18.73 and 22.61 per cents, respectively, of their initial amounts after 150 days of decomposition. Elevated CO₂-grown rice residues were found to be associated with higher values over the ambient CO₂-grown residues at all stages of sampling. Thus, the extent of decrease in weight was significantly higher under ambient CO₂ concentration. Hence, Elevated CO₂-grown rice residues were found to decompose at a slower rate compared to ambient CO₂-grown residues. This trend was clearly visible at all stages of sampling.

b) Carbon content

The average values of the per cent carbon composition of RA and RE at different stages of sampling are expressed in Figure 98.

As the decomposition proceeded, there was a decrease in the per cent carbon contents in both ambient (RA) and elevated (RE) CO₂-grown rice residues. The initial status of carbon content of both the residues are given in Table 5. Ambient CO₂-grown rice residues contained 41.28 per cent carbon, while elevation of CO₂ was found to increase its value to 42.26 per cent calculated on dry weight basis.

During the process of decomposition, the per cent carbon composition of RA decreased to 37.63 after 150 days inside the nylon bags. In case of RE, it decreased to 38.61 per cent after the same period. Up to 75 days of initial sampling, RE was found to contain significantly higher carbon. Subsequently the difference of carbon contents between the two types of residues narrowed and became non-significant. At around 135 days after start of decomposition, the values were almost identical.

c) Nitrogen content

Average nitrogen contents of RA and RE at different times of sampling during decomposition are shown in Figure 99. As decomposition proceeded, there was a decrease in the per cent nitrogen contents of both RA and RE.

Fig. 97. Amount (g) of ambient CO₂- (RA) and elevated CO₂-grown (RE) rice residues remaining in litterbags during different days of decomposition

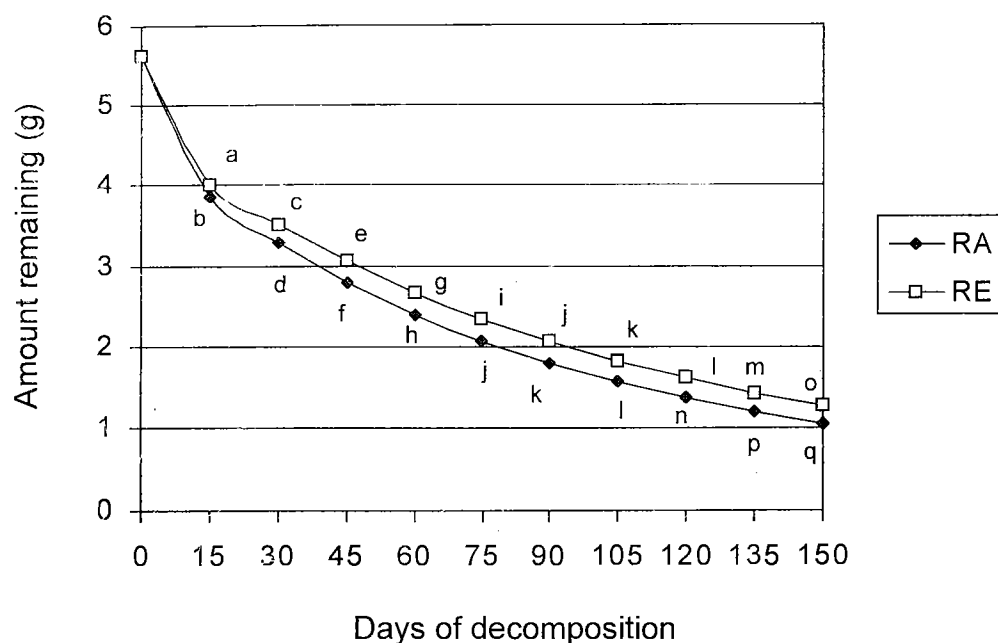
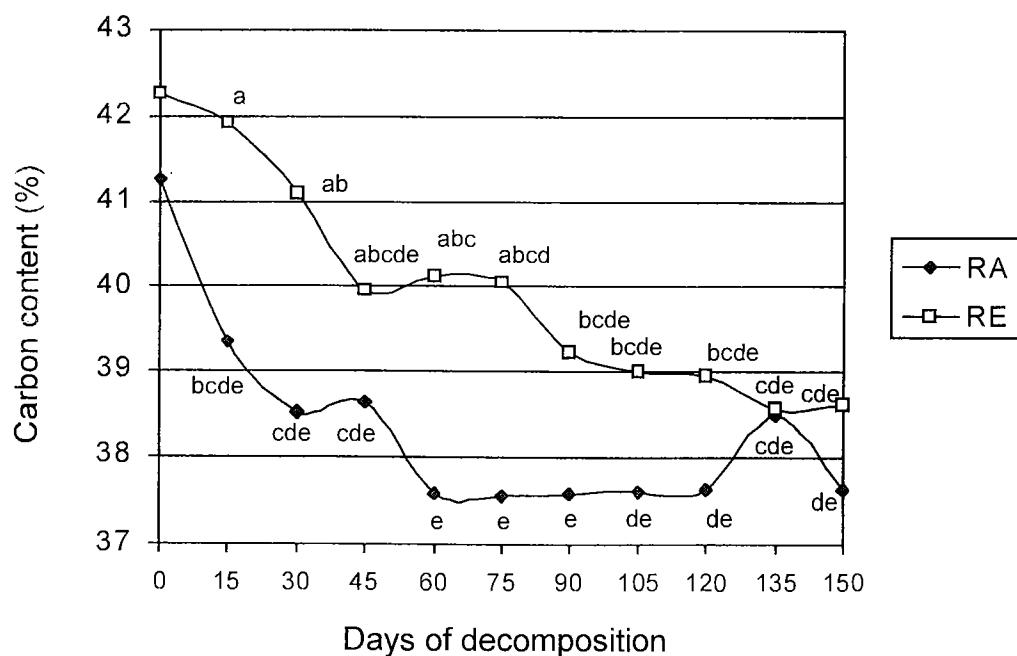


Fig. 98. Carbon contents (per cent) of ambient CO₂- (RA) and elevated CO₂-grown (RE) rice residues remaining in litterbags at different days of decomposition



The differences between any two values with any common alphabet within figures not statistically significant and *vice versa*

Fig. 99. Nitrogen contents (per cent) of ambient CO_2 - (RA) and elevated CO_2 -grown (RE) rice residues remaining in litterbags at different days of decomposition

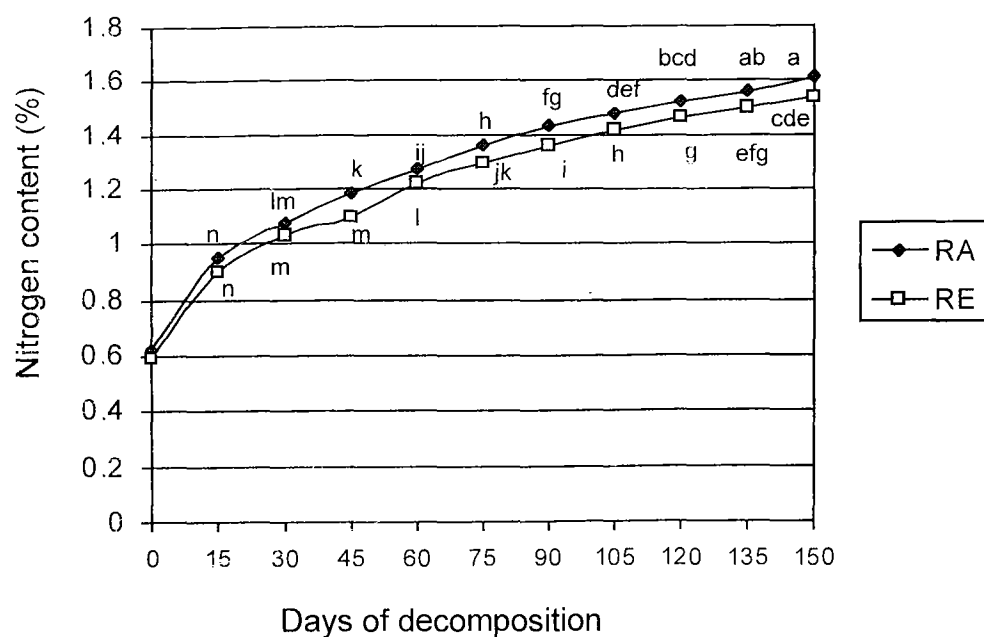
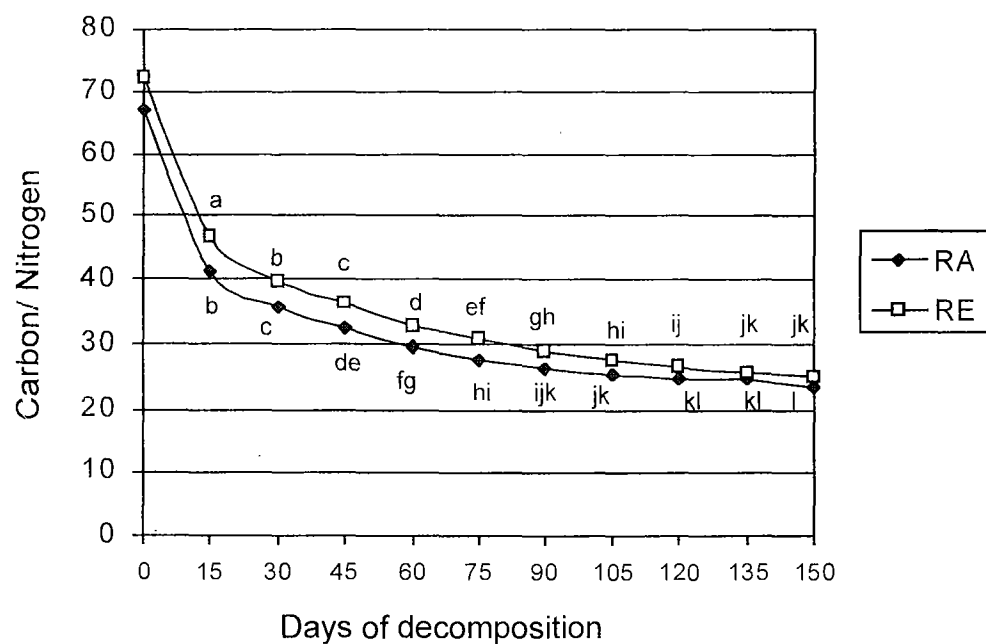


Fig. 100. The C:N ratio of ambient CO_2 - (RA) and elevated CO_2 -grown (RE) rice residue remaining in litterbags at different days of decomposition



The differences between any two values with any common alphabet within figures not statistically significant and *vice versa*

The per cent nitrogen contents of RA was higher when compared to the values associated with RE at various times of sampling during decomposition. The initial composition was also higher in RA over RE (Table 5). However there was no any significant difference between the two with respect to the per cent nitrogen content up to 30 days of decomposition. Afterwards, the per cent nitrogen contents of RA was significantly higher than RE which continued till the end of decomposition study.

d) C:N ratio

The C:N ratios of RA and RE during the process of decomposition inside the litterbags are given in Figure 100. It is evident that C:N ratios of the residues decreased as decomposition proceeded. There was a sharp decline in C:N ratio during the first 30 days of decomposition for both RA and RE and subsequently the decrease was gradual as decomposition proceeded.

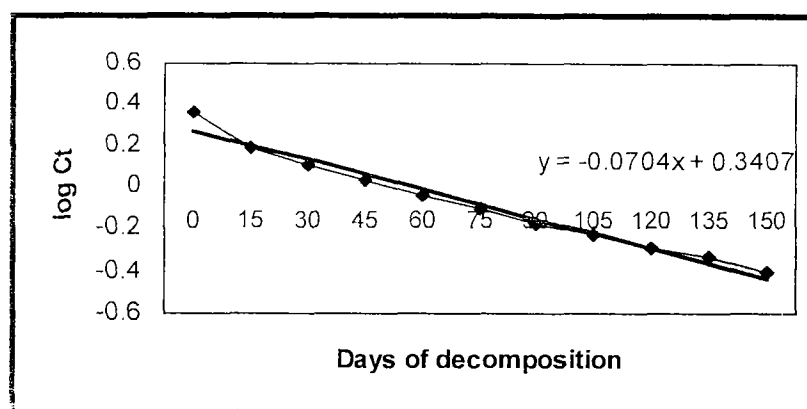
At all times of sampling during decomposition, RE was found to be associated with significantly higher C:N ratios over RA. Maintenance of smaller C:N ratio of RA during decomposition indicates possibility of faster rate of mineralization in comparison to RE. Usually when a high C:N material is incorporated into soil, the initial immobilization is followed by mineralization as the residues approach a break-even point of C:N ratio. Since RA was found to have lower C:N ratios at all times of sampling, the attainment of such break even point of C:N would be reached sooner. Hence the lower C:N ratios of RA in comparison to RE at all stages of decomposition has enormous consequences in nitrogen cycling in soil.

e) Kinetics of decomposition of RA and RE

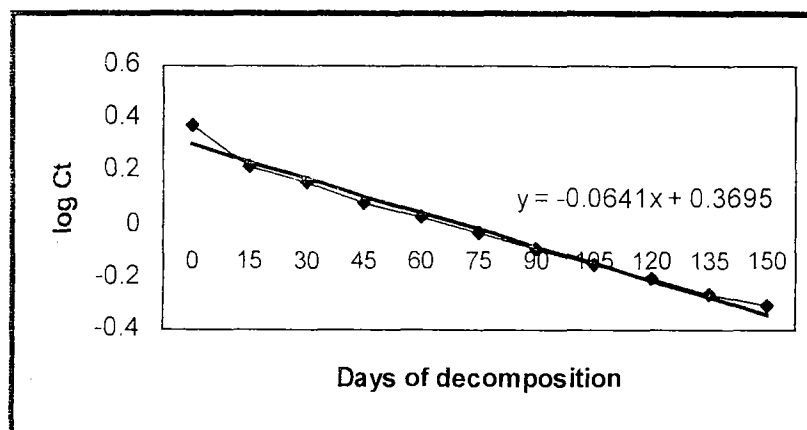
The graphical representations of logarithm of the amounts of plant carbon (C_t) remaining inside the litterbags at different times of sampling and best-fit trend lines (straight line) during decomposition are shown in Figure 101. Comparison of slope values indicated slower decomposability of RE over RA. The equations of straight lines fitted into the $\log C_t$ vs. time plots of RA and RE were $y = -0.0704x + 0.3407$ and $y = 0.0641x + 0.3695$, respectively. Thus the slope of the lines, indicating rate of decomposition of the residue decreased from 0.0704 for RA to 0.0641 (8.95% decrease) for RE when high CO_2 was prevailed during crop growth. Hence elevation of atmospheric CO_2 in

Fig. 101. Kinetics of decomposition of ambient CO₂- (RA) and elevated CO₂- (RE) grown rice residues

a) RA



b) RE



C_t : Amount of plant carbon remaining in rice residues within the litterbags at various stages of decomposition

microenvironment of the crop was found to decrease the decomposability of rice residues by about nine per cent.

4.3.1.2 Soil parameters

To analyze the impact of residue decomposition in soil, samples were analysed for total organic carbon, MBC, ammoniacal and nitrate nitrogen contents.

a) Total organic carbon

Average values of total organic carbon in soils at different times of sampling during decomposition of RA and RE are given in Figure 102.

The soil used for the experiment had an initial carbon value of 0.601 per cent (Table 4). Total organic carbon in soil showed an increasing trend (though non-significant), as the decomposition progressed, both in case of RA and RE. Moreover, in absolute terms regarding the values of organic carbon contents, the treatments with RA always recorded higher than RE treatments, though the difference was not statistically significant at any point of sampling. Nevertheless, it gives a clear indication that such differences might become significant in long run when such residues are continued to be added for years together.

The extent of increase in organic carbon values at different sampling times during decomposition were found to be higher during decomposition of RA. *ie.*, at all times of sampling during decomposition, RA was found to be associated with higher organic carbon in soil. This reiterated the faster decomposition of RA over RE.

b) Microbial biomass carbon (MBC)

Average values of MBC in soil at different times of sampling during the decomposition of RA and RE maintained at ambient and elevated CO₂ conditions are graphically represented in Figure 103.

The soil initially had a MBC content of 143.5 mg kg⁻¹ (Table 4), which got increased when the litterbags were inserted and allowed to decompose. The MBC values of both RA and RE treatments exhibited a very sharp increase during initial phase of decomposition in both cases. Subsequently, the values recorded decrease till the end of decomposition study. Such decreases were significant at every stage of sampling for both the kinds of substrates.

Fig. 102. Total soil organic carbon (per cent) during various stages of decomposition of ambient CO₂- (RA) and elevated CO₂-grown (RE) rice residues in litterbags placed in ambient and elevated phytotron chambers

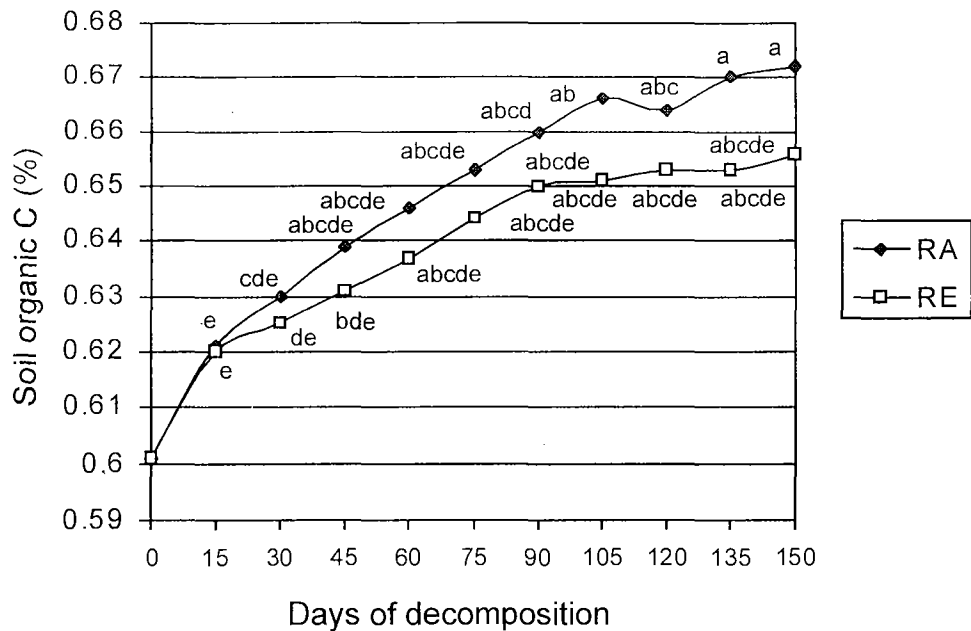
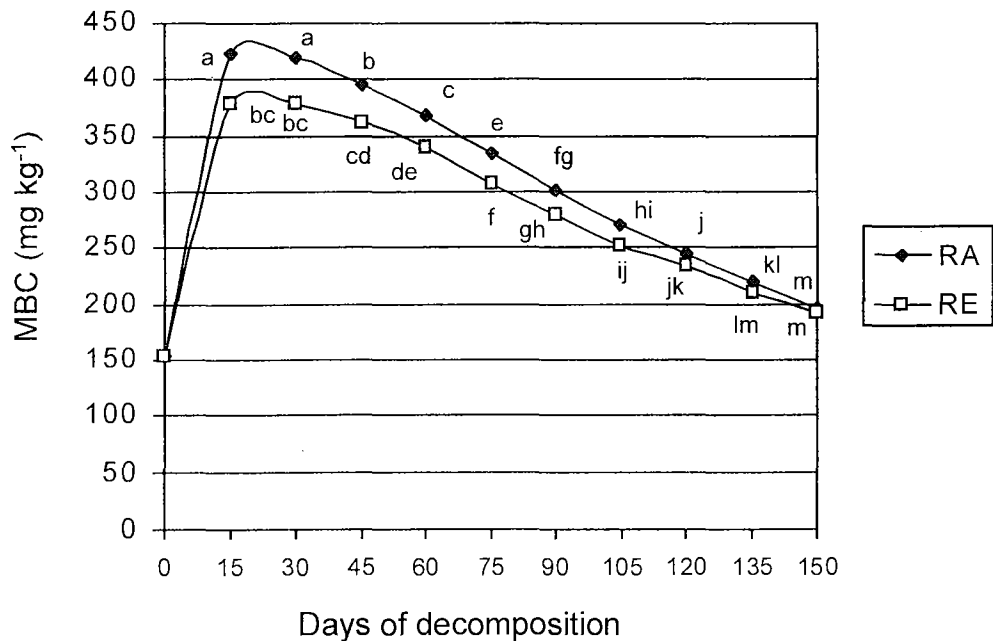


Fig. 103. Microbial biomass carbon (MBC, mg kg⁻¹) in soil during decomposition of ambient CO₂- (RA) and elevated CO₂-grown (RE) rice residues in litterbags placed in ambient and elevated phytotron chambers



The differences between any two values with any common alphabet within figures are not statistically significant and *vice versa*

When compared between two residues, MBC in soil, with RA was found to be higher than that with RE till first 75 days of decomposition. Subsequently, the difference between RA and RE got narrowed down and became non-significant. Values were almost identical at the end of decomposition study.

c) Ammoniacal nitrogen

Data pertaining to ammoniacal nitrogen contents in soil at different times of sampling during decomposition of RA and RE are presented in Figure 104.

Ammoniacal nitrogen content in soil first exhibited a very sharp decline from an initial value of 40.3 kg ha^{-1} during the first 15 days of decomposition. After the abrupt decline, there was a gradual increase till 90 days of decomposition, which subsequently leveled off. Towards the final stages (after 120-150 days) of decomposition a slight decrease in the value was observed during the decomposition of both the residues (RA and RE).

With relation to the kind of residues incorporated (RA and RE) except during 30-90 days of decomposition, the average values of the treatments were at par in different times of sampling. During the above referred period, soils with RA always recorded higher values over soils with RE.

The initial phase of decline in ammoniacal nitrogen indicate the process of immobilization, while subsequent increase is an indication of the process of mineralization. However, such increase could not be sustained till end due to subsequent nitrification of the ammoniacal nitrogen. The transition from immobilization to mineralization, for both RA and RE has occurred around 30 days of decomposition as after that $\text{NH}_4\text{-N}$ content in soils increased in both the cases. The slight decreases in this pool observed towards the final stage of decomposition indicate the rapid conversion of ammoniacal nitrogen to nitrate form through the process of nitrification.

d) Nitrate nitrogen

Nitrate nitrogen contents in soil at different times of sampling during decomposition of RA and RE in litterbags are presented in Figure 105.

In contrast to $\text{NH}_4\text{-N}$, the initial decrease in $\text{NO}_3\text{-N}$ contents of both the soils (up to 30 days of decomposition) were very gradual and not necessarily

Fig. 104. Ammoniacal nitrogen (kg ha^{-1}) in soil during various stages of decomposition of ambient CO_2 - (RA) and elevated CO_2 -grown (RE) rice residues in litterbags placed in ambient and elevated phytotron chambers

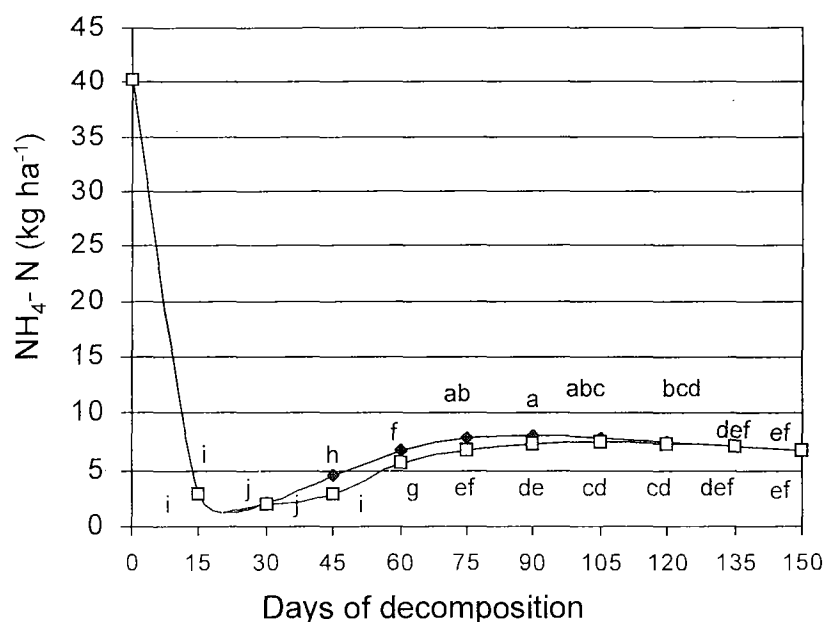
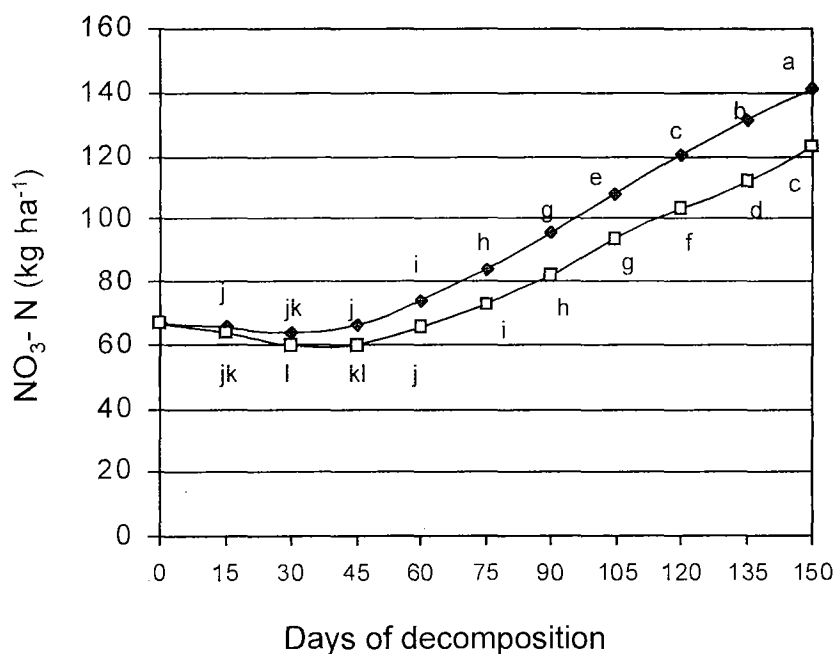


Fig. 105. Nitrate nitrogen (kg ha^{-1}) in soil during various stages of decomposition of ambient CO_2 - (RA) and elevated CO_2 -grown (RE) rice residues in litterbags placed in ambient and elevated phytotron chambers



The differences between any two values with any common alphabet within figures are not statistically significant and *vice versa*

significant. Further, beyond 45 days of decomposition $\text{NO}_3\text{-N}$ contents increased sharply which continued till the end of decomposition study. While initial phase of decrease indicates process of immobilization, subsequent increase was clearly due to mineralization. As the $\text{NH}_4\text{-N}$ kept on oxidizing to $\text{NO}_3\text{-N}$, its content continued to increase till end.

The experimental soil initially contained 60.7 kg ha^{-1} of nitrate nitrogen. The absolute values of nitrate nitrogen were higher in soil with RA over those with RE in litterbags at all stages of sampling from 30 days onwards. This superiority of RA with respect to the increase in N release can be ascribed to the higher nitrogen composition of RA compared to RE, thus triggering faster rate of N mineralization.

4.3.1 Decomposition kinetics of ambient and elevated CO_2 -grown wheat residues

Ambient (WA) and elevated CO_2 -grown (WE) wheat residues were also allowed to decompose for a period of 150 days in litterbags inserted into soil in pots. The results of the decomposition study are presented here.

4.3.1.1 Residue parameters

a) Amount of residue remaining inside the litterbags

The amount of ambient and elevated CO_2 -grown wheat residues remaining inside the litterbags at different times of sampling during decomposition are given in Figure 106.

WA and WE got reduced to 26.9 and 29.5 per cent, respectively, of their initial amount (5.625 g), after 150 days of decomposition inside the litterbags. The weight decrease was significantly higher under ambient CO_2 concentration when compared to elevated CO_2 between 45 and 60 days of decomposition, on 90th day of decomposition, and again at the last day (150th day) of sampling. On other days the difference was non-significant. Nevertheless, this indicated that WE decomposed at a slower rate compared to WA. However, This trend was much clear in case of rice residues. With relation to the days of decomposition, in both the substrates, the amount remaining in litterbags reduced with time; the difference being significant between each stages of sampling (except the last sampling with WE).

Fig. 106. Amount (g) of ambient CO₂- (WA) and elevated CO₂-grown (WE) wheat residues remaining in litterbags during different days of decomposition

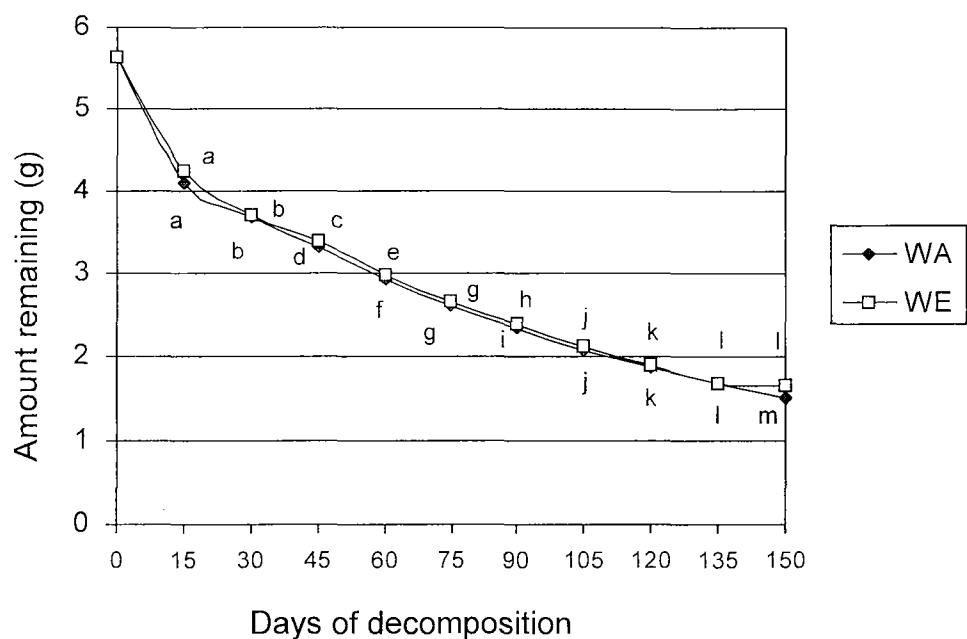
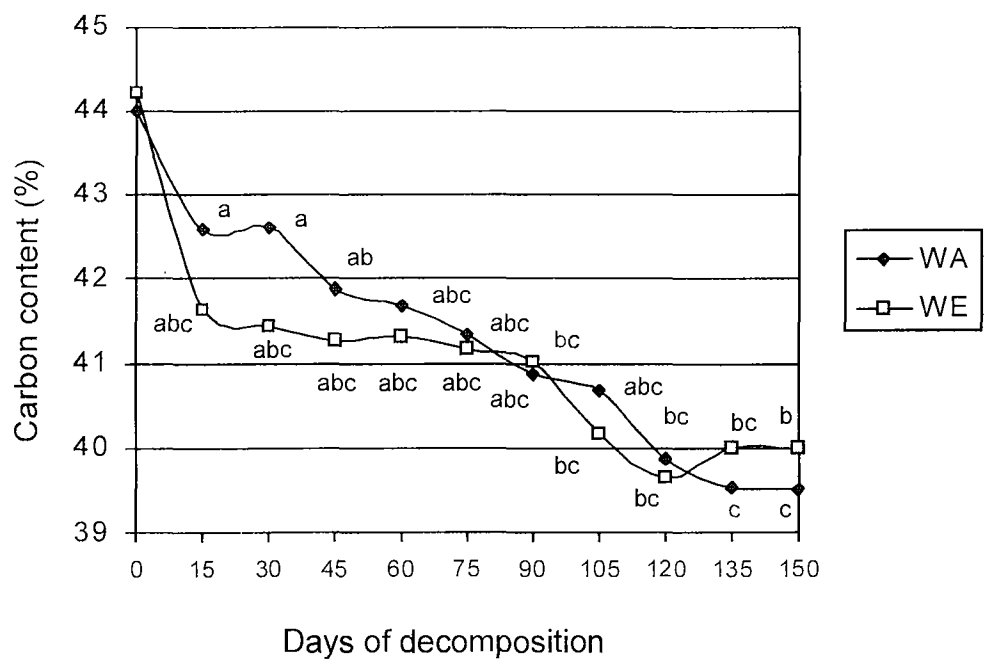


Fig. 107. Carbon content (per cent) of ambient CO₂- (WA) and elevated CO₂-grown (WE) wheat residues remaining in litterbags at different days of decomposition



The differences between any two values with any common alphabet within figures are not statistically significant and *vice versa*

b) Carbon content

Values pertaining to carbon concentration in ambient and elevated CO₂-grown wheat residues at different stages of decomposition are expressed in Figure 107.

During decomposition per cent carbon content of both the types of residues decreased. However, such decrease was not necessarily significant between two successive stages of sampling. Initially, WA contained 44 per cent carbon, while elevation of CO₂ was found to increase its value to 44.21 per cent in wheat residues. During the process of decomposition, carbon content in WA decreased to 39.5 per cent after 150 days, while in WE it decreased to 40.0 per cent. Though ambient CO₂-grown wheat material (WA) was found to contain higher amount of carbon, the difference with WE was not significant at any time of sampling. Moreover at the end of decomposition (150th day) the C content was significantly higher in WE over WA.

c) Nitrogen content

Nitrogen composition of WA and WE at different times of sampling during decomposition inside the litterbags are shown Figure 108. As decomposition proceeded, there was an increase in the per cent nitrogen contents of both WA and WE. The absolute values of nitrogen content in WA was higher when compared to the composition of WE, though the differences were not statistically significant except on 45th day of decomposition. In comparison to WE, initial N concentration was also higher in WA (Table 5).

d) C:N ratio

The values of C:N ratios of WA and WE during the process of decomposition inside the litterbags are given in Figure 109.

It is evident that C:N ratio of the residues decreased as decomposition proceeded. There was a sharp decline in the C:N ratio during the early 30 days of decomposition in both WA and WE, and the rate subsequently eased out as the decomposition proceeded.

Before the start of decomposition, the C:N ratio of WE was more than WA. This might have been the primary reason for slower decomposition of WE as manifested in terms of rate of reduction of weight, carbon and nitrogen contents. However, except on 15th, 45th and 75th days of decomposition, the

Fig. 108. Nitrogen content (per cent) of ambient CO₂- (WA) and elevated CO₂-grown (WE) wheat residues remaining in litterbags at different days of decomposition

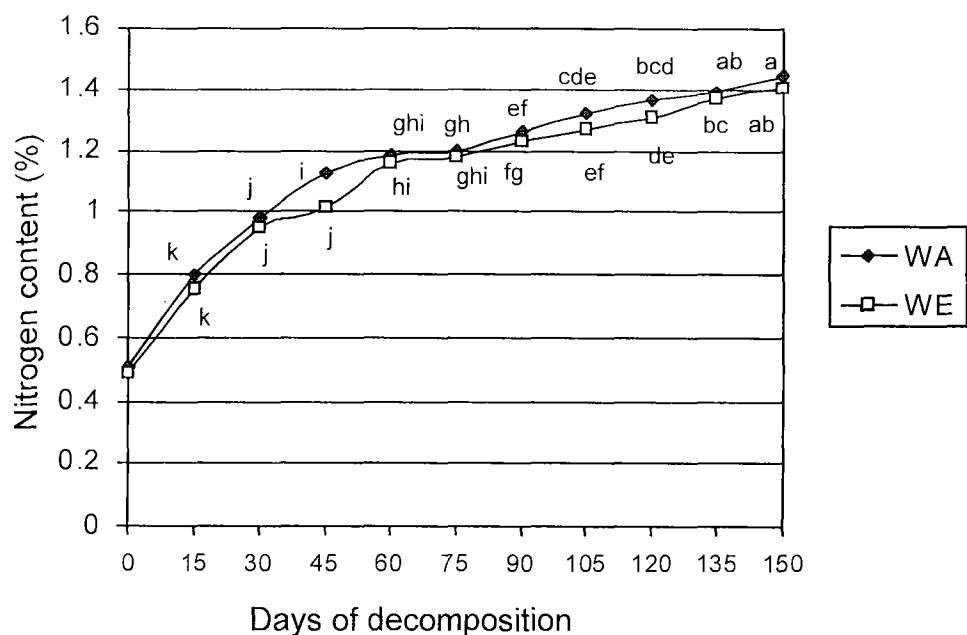
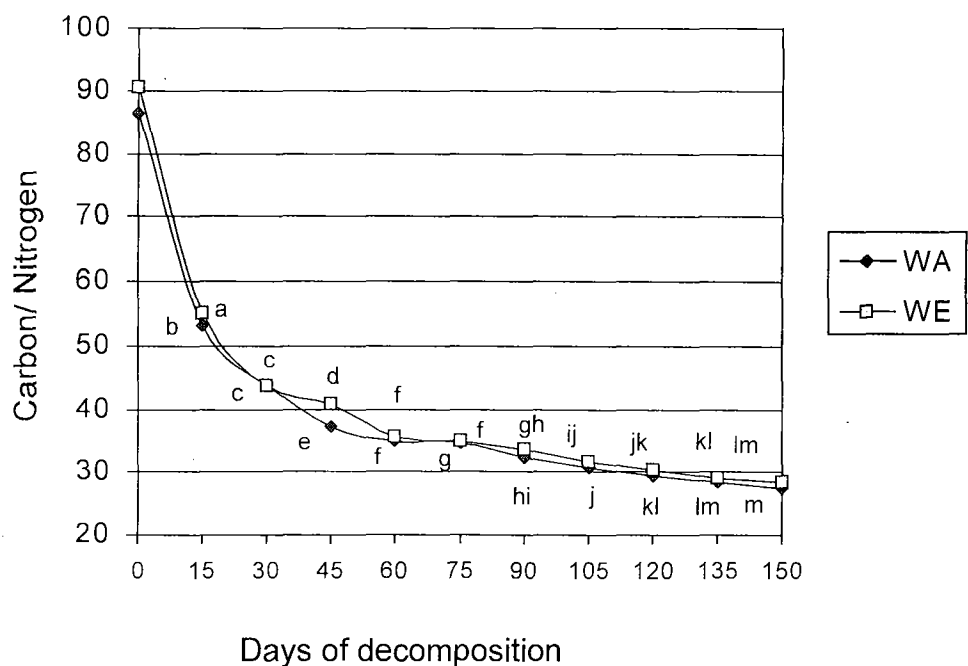


Fig. 109. The C:N ratio of ambient CO₂- (WA) and elevated CO₂-grown (WE) wheat residues remaining in litterbags at different days of decomposition



The differences between any two values with any common alphabet within figures are not statistically significant and *vice versa*

two types of residues had similar C:N ratio during the decomposition. Nevertheless, values of the ratio (in absolute terms) were higher in WE at all stages of decomposition. This trend if become significant on continuous exposure to a naturally managed ecosystem, might have huge consequence on nutrient cycling.

e) Kinetics of decomposition of WA and WE

The graphical representations of logarithm of the amount of plant carbon (C_t) remaining inside the litterbags with time of decomposition are given in Figure 110. The equations of straight lines fitted into the $\log C_t$ vs time plots of WA and WE were $y = -0.0565x + 0.3814$ and $y = -0.054x + 0.3748$ respectively. Thus the slope of the lines, indicating rate of decomposition of the residue, decreased from 0.0565 for WA to 0.054 (a 4.4 % decrease) for WE. Hence elevation of atmospheric CO_2 in the microenvironments of the crop was found to decrease the decomposability of the wheat residues by 4.4 per cent.

4.3.2.2. Soil parameters

To analyze the impact of residue decomposition in soil, samples were analyzed for total organic carbon, MBC, ammoniacal and nitrate nitrogen contents during decomposition of wheat residues.

a) Total organic carbon

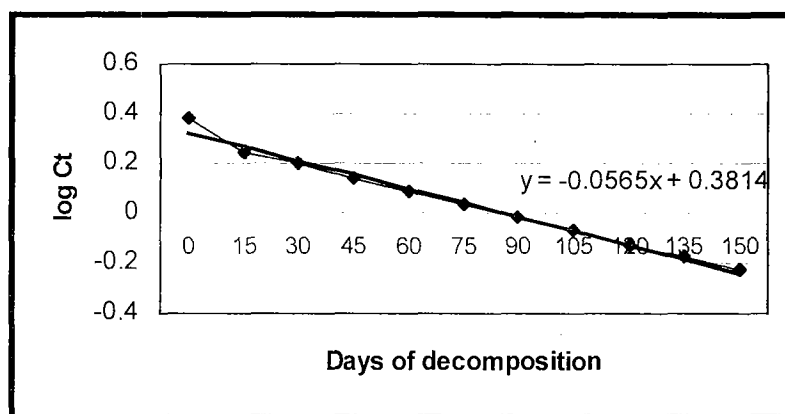
Values pertaining to total organic carbon content in soil at different times of sampling during decomposition of WA and WE are given in Figure 111.

The soil used for the experiment had an initial carbon content of 0.601 per cent (Table 4). Total organic carbon in soil showed an increasing trend, as the decomposition progressed, though the changes were statistically non-significant.

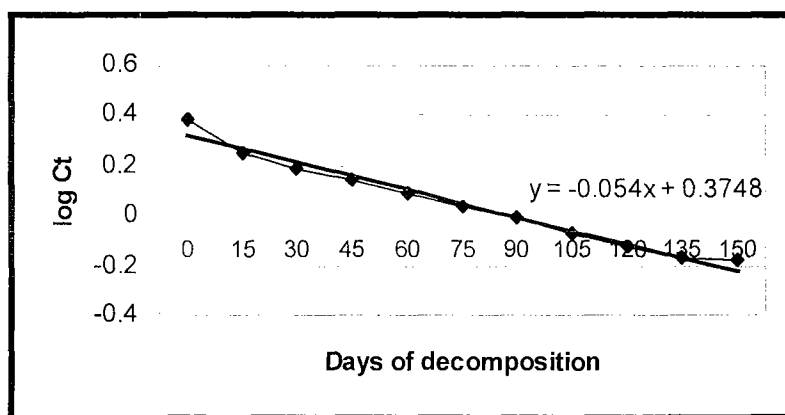
There was no difference either between the two types of residues. The extent of increase in organic carbon values at different time intervals during decomposition was found to be similar for both WA and WE. In absolute terms, soil with WA had higher values than that with WE. Such a trend reiterated the tendency of faster decomposition of WA over WE.

Fig. 110. Kinetics of decomposition of ambient CO₂- (WA) and elevated CO₂- (WE) grown wheat residues

a) WA



b) WE



C_t : Amount of plant carbon remaining in rice residues within the litterbags at various stages of decomposition

Fig. 111. Total soil organic carbon (per cent) during various stages of decomposition of ambient CO₂- (WA) and elevated CO₂-grown (WE) wheat residues in litterbags placed in ambient and elevated phytotron chambers

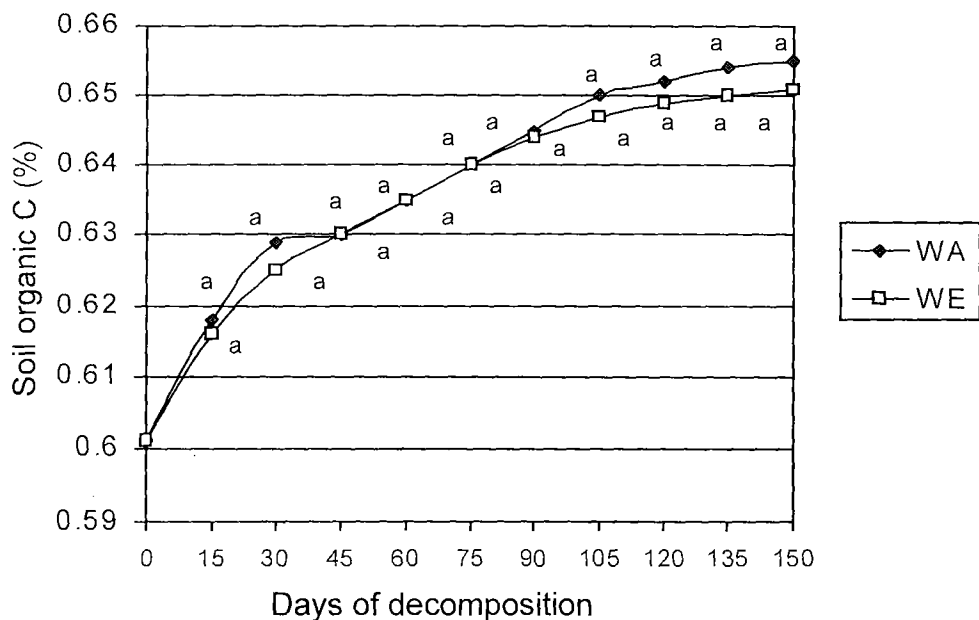
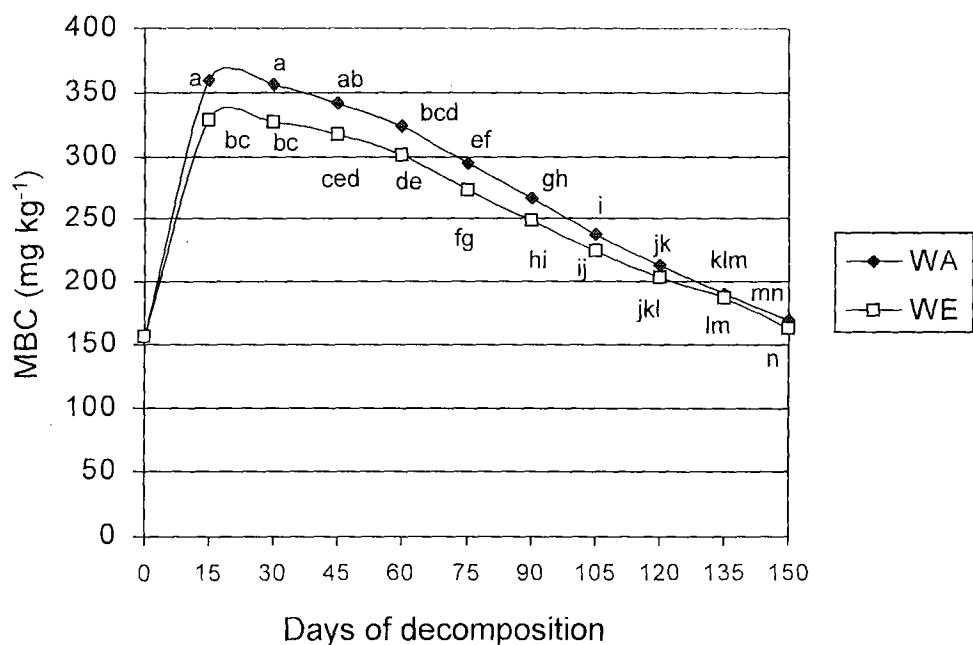


Fig. 112. Microbial biomass carbon (mg kg⁻¹) in soil during decomposition of ambient CO₂- (WA) and elevated CO₂-grown (WE) wheat residues in litterbags placed in ambient and elevated phytotron chambers



The differences between values with any common alphabet within figures are not statistically significant and *vice versa*

b) Microbial biomass carbon

Data pertaining to MBC content in soil at different times of sampling during the decomposition of WA and WE maintained in ambient and elevated CO₂ conditions, respectively is graphically represented in Figure 112.

The experimental soil initially had a MBC content of 143.5 mg kg⁻¹ (Table 5), which increased sharply during first fifteen days of decomposition when the litterbags containing both the types of wheat residues were inserted and allowed to decompose. Subsequently, the MBC content in soil decreased from 45th day onwards till the end of decomposition study.

When compared between the two residues, MBC in soil was found to be higher during first 45 days of decomposition of WA than that of WE. Thereafter no significant difference was observed between the soils incorporated with these residues. Elevation of CO₂ while growing the crop residues was found to reduce the ability of the residues to support microbial activity in soil during the initial phase of its decomposition. This corroborates the earlier finding of relatively lower rate of decomposition of WE when compared to WA.

c) Ammoniacal nitrogen

The average ammoniacal nitrogen contents in soil at different times of sampling during decomposition of WA and WE are presented in Figure 113.

As in case of rice residues, ammoniacal nitrogen content in soil first exhibited a very sharp decrease for both WA and WE, from an initial value of 40.3 kg ha⁻¹. After this abrupt decline, an increase in value was observed from 60 to 105 days of decomposition of both residues, which was maintained and slightly decreased near the final stage of decomposition. Such trend was observed during the decomposition of rice residues also. The initial phase of decline in ammoniacal nitrogen indicates the process of immobilization, while subsequent increase indicates mineralization. The break-even point that indicates the transition from immobilization to mineralization for both WA and WE occurred around 45 days after start of decomposition. Except 60th day of decomposition, ammoniacal N contents were similar in both the soils incorporated with WA or WE.

Fig. 113. Ammoniacal nitrogen (kg ha^{-1}) in soil during various stages of decomposition of ambient CO_2 - (WA) and elevated CO_2 -grown (WE) wheat residues in litterbags placed in ambient and elevated phytotron chambers

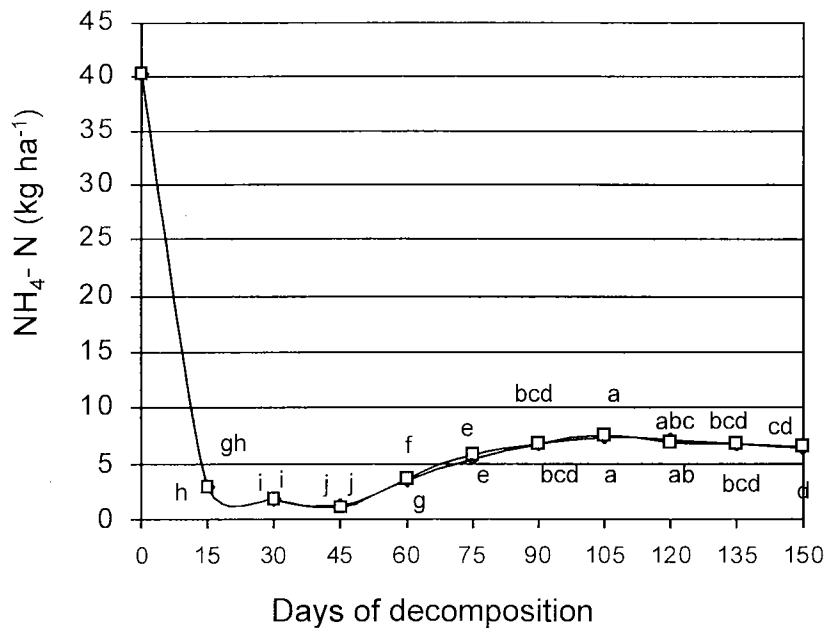
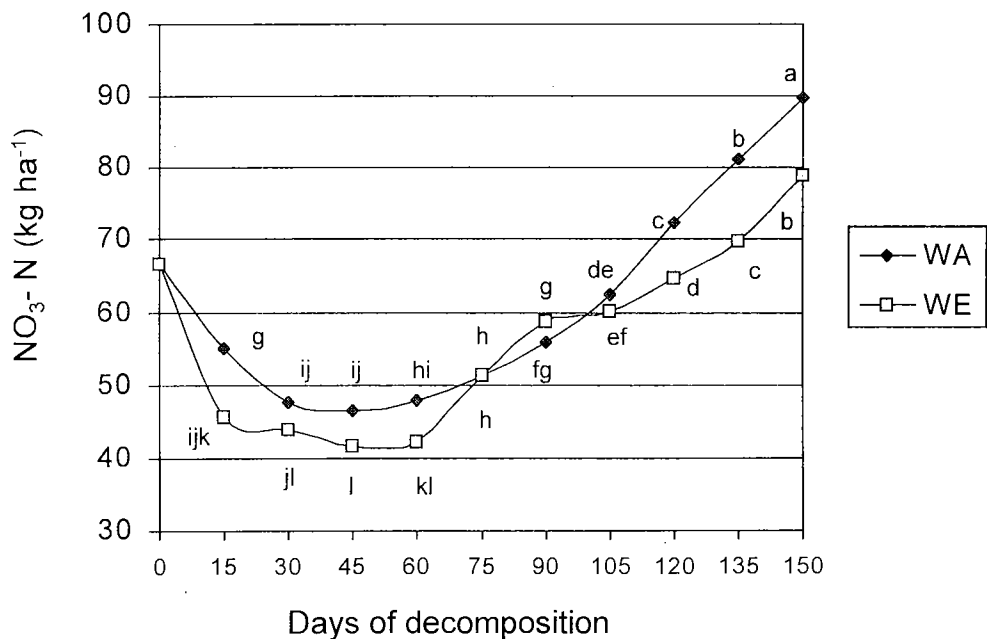


Fig. 114. Nitrate nitrogen (kg ha^{-1}) in soil during various stages of decomposition of ambient CO_2 - (WA) and elevated CO_2 -grown (WE) wheat residues in litterbags placed in ambient and elevated phytotron chambers



The differences between any two values with any common alphabet within figures are not statistically significant and *vice versa*

d) Nitrate nitrogen

The average values of nitrate nitrogen contents in soil at different times of sampling during decomposition in litterbags are presented in Figure 114.

A trend similar to that found in case of rice residues was observed in wheat residues also with respect to the change in nitrate-N content in soil during decomposition. An initial gradual decrease in $\text{NO}_3\text{-N}$ content occurred during first 30 days of decomposition, which remained at its lowest till 60 days after start of decomposition, after which a gradual but continuous increase was observed till the end of decomposition period. The initial phase of decrease in nitrate nitrogen indicates the process of immobilization and the increase in nitrate nitrogen contents occurring at the later period of decomposition is an indication of net mineralization.

The absolute values of nitrate nitrogen were higher in soil with WA in litterbags over the corresponding values of WE except a brief period from 75th to 105th day of decomposition during which the values were at par. The soil initially contained 60.7 kg ha^{-1} of nitrate nitrogen. Though the initial values were same, a higher amount of nitrate nitrogen was released into soil during decomposition of WA. This superiority of WA expressed in terms of increased rate of N mineralization can be explained by the higher nitrogen content of WA (0.51 %) than WE (0.49%) (Table 5).

4.4 MODELLING EXPERIMENT

CERES model is a modification of the PAPRAN model. CERES-N simulates soil nitrogen transformations including mineralization, immobilization, nitrification and denitrification. Programme for the CERES model was created in FORTRAN language in MS-DOS mode. Mineralization and immobilization subroutine of the model simulates decay of two types of organic matter: fresh organic matter or residue material (FOM) and humus (HUM). The model was created in such away that at the beginning of simulation, FOM is divided into three pools: 20 per cent of FOM goes to carbohydrate (CARB), 70 per cent goes to cellulose (CELL) and the remaining 10 per cent to lignin (LIGN). The three pools decompose simultaneously, limited by a maximum rate constant of decomposition for each pool. In the original CERES-N, values for these maximum rate constants were obtained

from PAPRAN model. The original values were 0.2, 0.05 and 0.0085 day⁻¹ for CARB, CELL and LIGN, respectively (Table 53).

4.4.1 Modifications of CERES-N model

Experimental results of the decomposition study did not fit as such into the original CERES model. Certain modifications were done to make the model simulate decomposition of rice and wheat residues in ambient and elevated CO₂ conditions. The modifications were as follows:

- a) The original model assumes that nitrate nitrogen pool will be used for immobilization only after the ammoniacal nitrogen pool gets depleted. This assumption was not satisfied in our experiment and we had to change the model in a manner to include the proportional intake of both ammoniacal and nitrate nitrogen pools for immobilization. Taking in to account of the quantities of initial pools, the proportionality factors were incorporated.
- b) Another modification incorporated into the model was with respect to the limit of nitrification indicated by BB value in the programme. BB value indicates maximum nitrification rate. The maximum limit of this transition was initially noted in the model by a BB value of 0.8. But to simulate the decomposition in litterbags the BB value was changed to 0.6.
- c) The original values of rate parameters of CARB, CELL and LIGN, when fed into the model, the model values (output) deviated much from the experimental values associated with the decomposition of any of the residues taken for experiment in phytotron chambers. Hence, certain changes were made to those parameters and the modified values were found out from repeated runs of the model. The runs were made to simulate and match the predicted values with the observed values of the amount of residue remained in litterbags, soil organic carbon, ammoniacal and nitrate nitrogen contents in soil at different times of sampling during decomposition. Input values for these runs included amount of residue taken for decomposition (FOM), amount of nitrogen taken (FON, calculated from the per cent nitrogen content and FOM), initial soil organic carbon, mineralization rate constant of humus pool, initial ammoniacal and nitrate nitrogen contents in soil, soil moisture, wilting point, field capacity

Table 53. Modified decay parameters for the three plant residue pools in CERES model obtained by fitting to the experimental results

	Carbohydrate (day ⁻¹)	Cellulose (day ⁻¹)	Lignin (day ⁻¹)
Original CERES	0.8	0.05	0.0085
RA	0.38	0.01899	0.0035
RE	0.32	0.01691	0.00266
WA	0.31	0.01561	0.0013
WE	0.29	0.01508	0.0011

Table 54. Input values of different types of residues used for running the model

Input parameters	RA	RE	WA	WE
FOM (kg ha ⁻¹)	30,000	30,000	30,000	30,000
FON (kg ha ⁻¹)	184.5	176.7	153	146.7
Soil organic carbon (%)	0.601	0.601	0.601	0.601
Decay constant for HUM (day ⁻¹)	0.00005	0.00005	0.00005	0.00005
Ammoniacal N (kg ha ⁻¹)	66.7	66.7	66.7	66.7
Nitrate N (kg ha ⁻¹)	40.3	40.3	40.3	40.3
Soil temperature (°C)	24.7	24.5	24.2	24.1
Soil moisture (%)	26.98	25	26.07	25.50
Field capacity (%)	13	13	13	13
Wilting point (%)	25	25	25	25

and soil temperature. The modified decay parameters for the four types of residues arrived through this method are given in Table 53.

These modifications mentioned were incorporated and the values of different parameters at different times of sampling (15 days interval) as is followed for the decomposition study were predicted by feeding the initial values which included the same inputs as mentioned above. The input values were different for the four types of residue taken for decomposition (Table 54).

4.4.2 CERES-N simulation of the decomposition of RA

After necessary modifications as stated above, the CERES model was found to simulate the process of carbon mineralization from RA quite satisfactorily. The input values used for finding out the modifications in the structure of the model are given in Table 54. The modified values of decay parameters for CARB, CELL and LIGN were 0.38, 0.01899 and 0.0035 respectively. When these modifications were incorporated, observed and predicted values of weight of residue remaining inside the litterbags, total organic carbon in soil, ammoniacal and nitrate nitrogen in soil were close, which are graphically depicted in Figure 115.

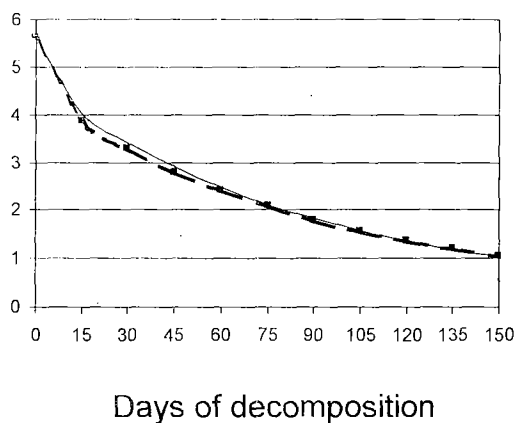
There was perfect consensus among the observed and predicted values of the amount of RA remaining inside the litterbags at different times of sampling during decomposition. The graphical representation of observed vs. predicted values are given in Fig 116a and the χ^2 value indicating the goodness of fit of the model for this set of data was 0.016.

The trend of increase in total organic carbon content in soil as the decomposition proceeded was indicated both by predicted and observed values (Fig. 115b). The extent of association between observed and predicted values were poorer than the previous case. The χ^2 value was observed to be 0.005 (Fig. 116b). In general, the measured (observed) values of organic carbon in soil were slightly higher than the predicted values throughout the period of decomposition (Fig. 115b).

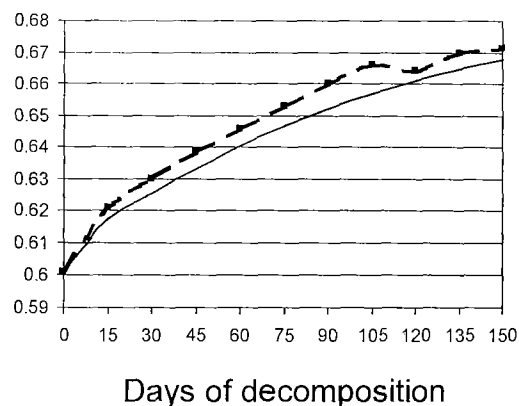
The nitrate and ammoniacal nitrogen contents in soil also showed consensus among the observed and predicted values associated with the decomposition of RA. As discussed in the previous section, the ammoniacal nitrogen content sharply decreased from an initial value of 40.3 kg ha⁻¹ during

Fig. 115. The predicted (solid line) and observed (dotted line) values of different parameters associated with the decomposition of ambient CO₂-grown rice (RA) residues under ambient atmospheric CO₂ condition

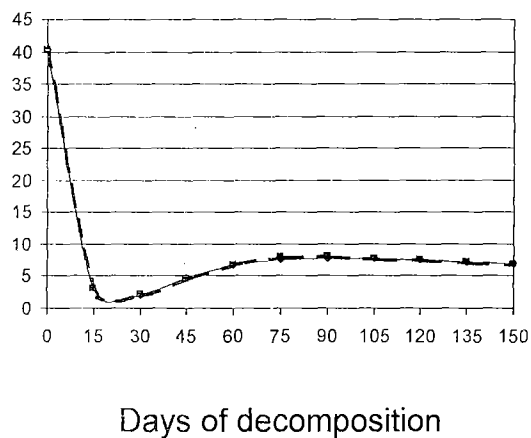
a) Amount remaining (g)



b) Soil organic C (%)



c) NH₄-N (kg ha⁻¹)



d) NO₃-N (kg ha⁻¹)

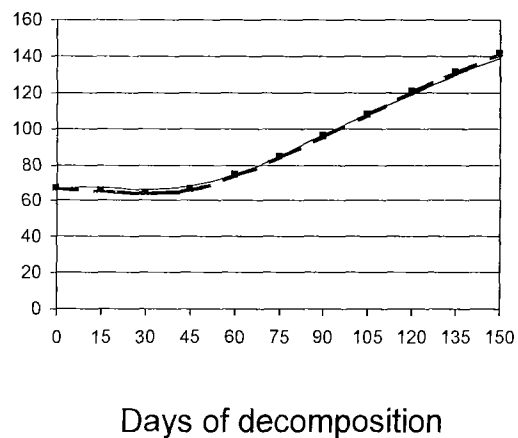
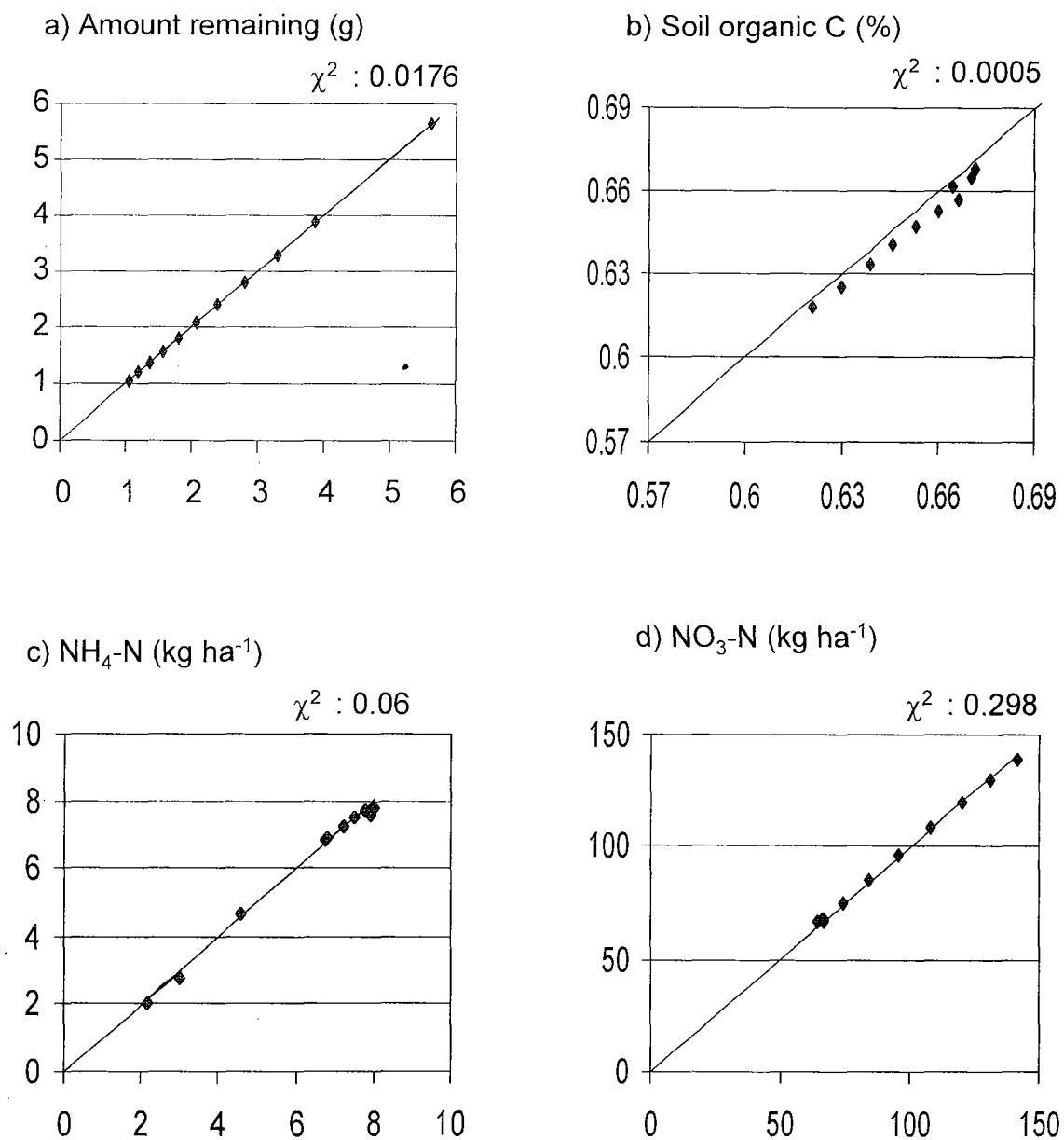


Fig. 116. Goodness of fit of observed (x-axis) and predicted (y-axis) values of different parameters associated with the decomposition of ambient CO₂-grown rice residues (RA) under ambient atmospheric CO₂ condition



the initial period of decomposition of the residue, followed by a gentle increase, and then a slight decrease (Fig. 115c). Both predicted and observed sets of values of ammoniacal nitrogen followed this trend in a similar fashion. Nitrate nitrogen content followed initial gentle decrease and then a gradual increase till end both in case of observed and predicted values, indicating immobilization and mineralization occurring in succession. The χ^2 values recorded among the predicted and observed data were 0.06 and 0.29 for the ammoniacal and nitrate nitrogen pools in soil, respectively (Fig. 116c and d). The values were higher compared to those explaining the parameters of amount of residue remaining and soil organic carbon.

4.4.3 CERES simulation of decomposition of RE

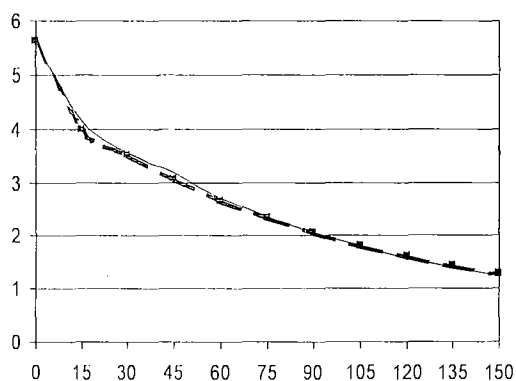
The ability of CERES-N subroutine to simulate mineralization processes during decomposition of RE was also evaluated. Model was modified and data were fit into the model by incorporating the changes in decay parameters of CARB, CELL and LIGN obtained through repeated run of the model. Upon modification, the observed data of amount remaining inside the litterbags, soil organic carbon, ammoniacal and nitrate nitrogen contents in soil was found to fit to the model. Such good consensus was obtained when the decay parameters of CARB, CELL and LIGN were changed to 0.32, 0.01691 and 0.00266, respectively, along with the other modifications mentioned earlier. After incorporation of these changes, the values of different parameters at different times of sampling (15 days interval) as is followed for the decomposition study were predicted by feeding the initial parameters, as given in Table 54.

The observed and predicted values of weight of residue remaining inside litterbags, soil organic carbon, ammoniacal and nitrate nitrogen in soil during decomposition of RE are shown in Figure 117 and the goodness of fit for observed and predicted data for these parameters are presented in Figure 118.

The amount of residue remaining inside the nylon bags declined sharply during initial period of decomposition of RE (Fig. 117a). This was observed in case of predicted values also. The observed vs. predicted plot

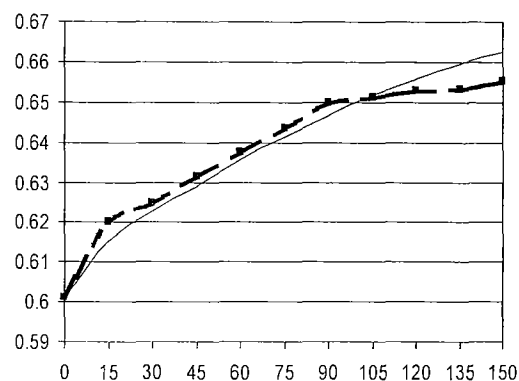
Fig. 117. The predicted (solid line) and observed (dotted line) values of different parameters associated with the decomposition of elevated CO₂-grown rice (RE) residues under elevated atmospheric CO₂ condition

a) Amount remaining (g)



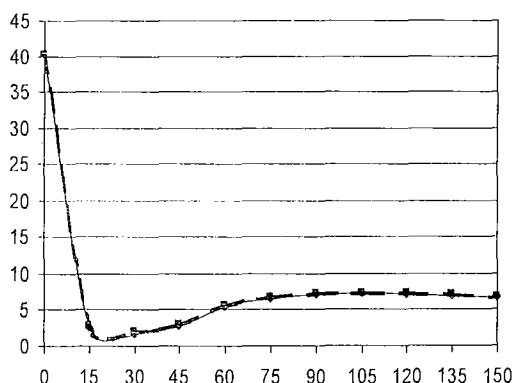
Days of decomposition

b) Soil organic C (%)



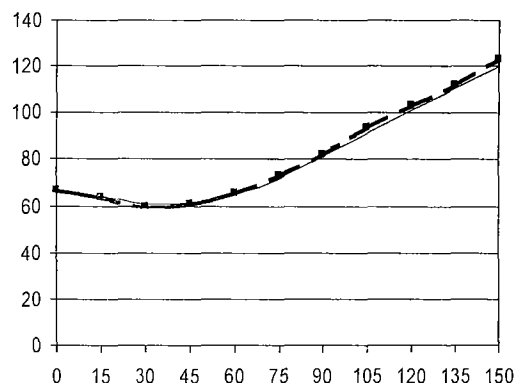
Days of decomposition

c) NH₄-N (kg ha⁻¹)



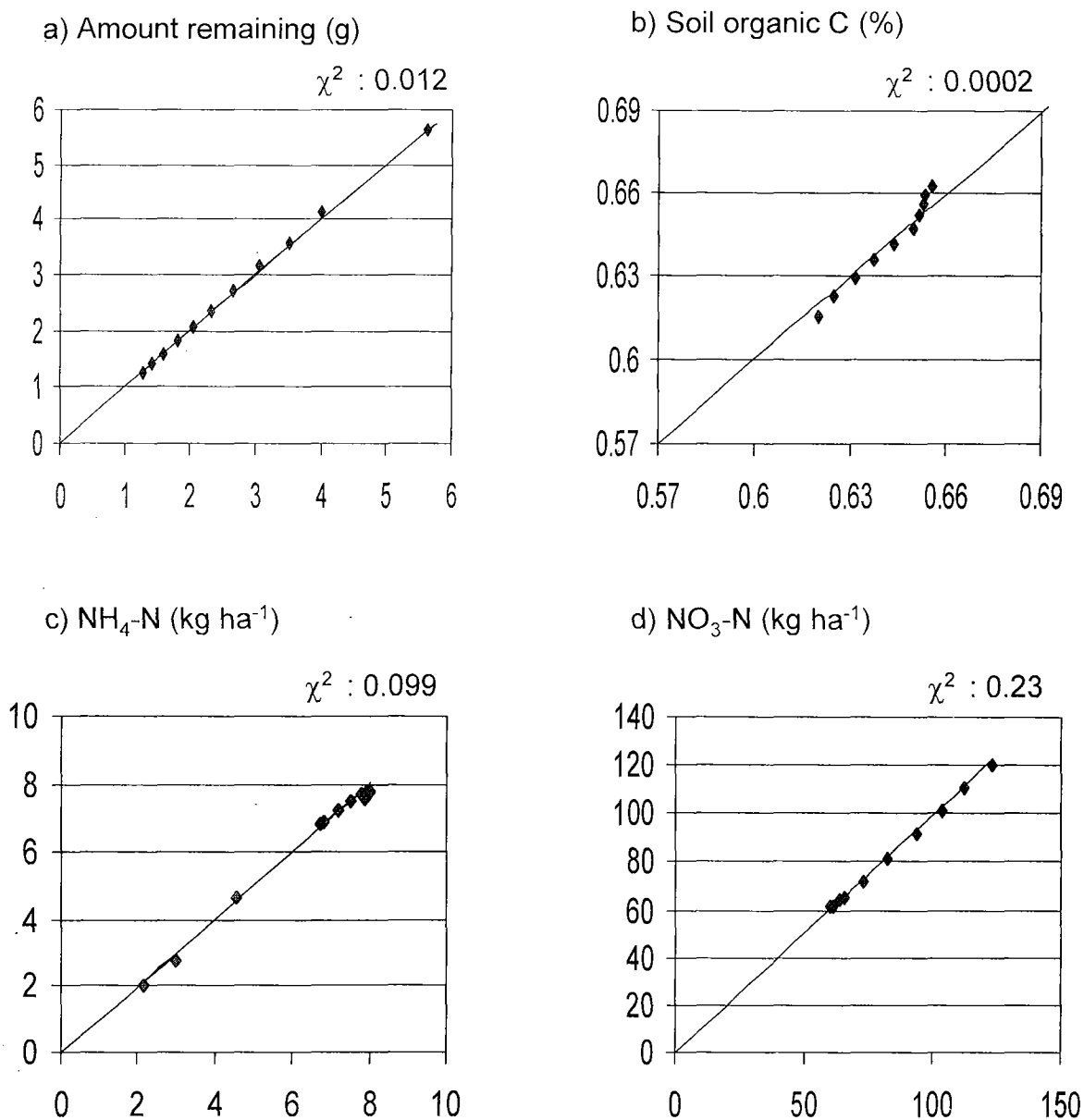
Days of decomposition

d) NO₃-N (kg ha⁻¹)



Days of decomposition

Fig. 118. Goodness of fit of observed (x-axis) and predicted (y-axis) values of different parameters associated with the decomposition of elevated CO₂-grown rice residues (RE) under elevated atmospheric CO₂ condition



showed a clear agreement between the two sets of values with χ^2 value of 0.0085 (Fig. 118a).

6.012 In case of soil organic carbon, both observed and predicted values exhibited an increasing trend. The data was found to fit well to the model with a χ^2 value of 0.0002. The lower χ^2 values specified the effectiveness of CERES-N to simulate C mineralization during decomposition of RE (Fig. 118b).

Ammoniacal and nitrate nitrogen in soil decreased from their initial values when decomposition of residues started. This indicates the phase of net immobilization. Later net mineralization phase set in which resulted into the increases in inorganic nitrogen pools. These trends were followed as such by the predicted as well as observed values of these nitrogen pools. The χ^2 values for ammoniacal and nitrate nitrogen in soil during decomposition of RE were 0.094 and 0.23, respectively. It further means that the values related to ammoniacal nitrogen content in soil was found to fit more closely to the model in comparison to nitrate nitrogen values. The values of both pools were found to cluster around the 1:1 line in the predicted vs observed diagram (Fig. 118c and d). Thus modified CERES could efficiently simulate the process of N mineralization during decomposition of RE.

4.4.4 CERES simulation of decomposition of WA

Evaluation of the model to predict C and N mineralization during decomposition of WA was also attempted. Input values used in relation to the modifications in the structure of the model are given in Table 54. The data were found to fit to the model when modifications were applied to the decay parameters of CARB, CELL and LIGN. The respective values were 0.31, 0.01561 and 0.0013 day⁻¹. When these changes were incorporated, CERES-N was found to be very effective in simulating carbon and nitrogen mineralization processes in soil during decomposition of WA.

Predicted and observed values of the amount of WA remaining inside nylon bags, soil organic carbon, ammoniacal and nitrate nitrogen in soil during decomposition of WA are given in Figure 119. The distributions of observed vs predicted values of these parameters around 1:1 line are depicted in Figure 120.

Fig. 119. The predicted (solid line) and observed (dotted line) values of different parameters associated with the decomposition of ambient CO₂-grown wheat residues (WA) under ambient atmospheric CO₂ condition

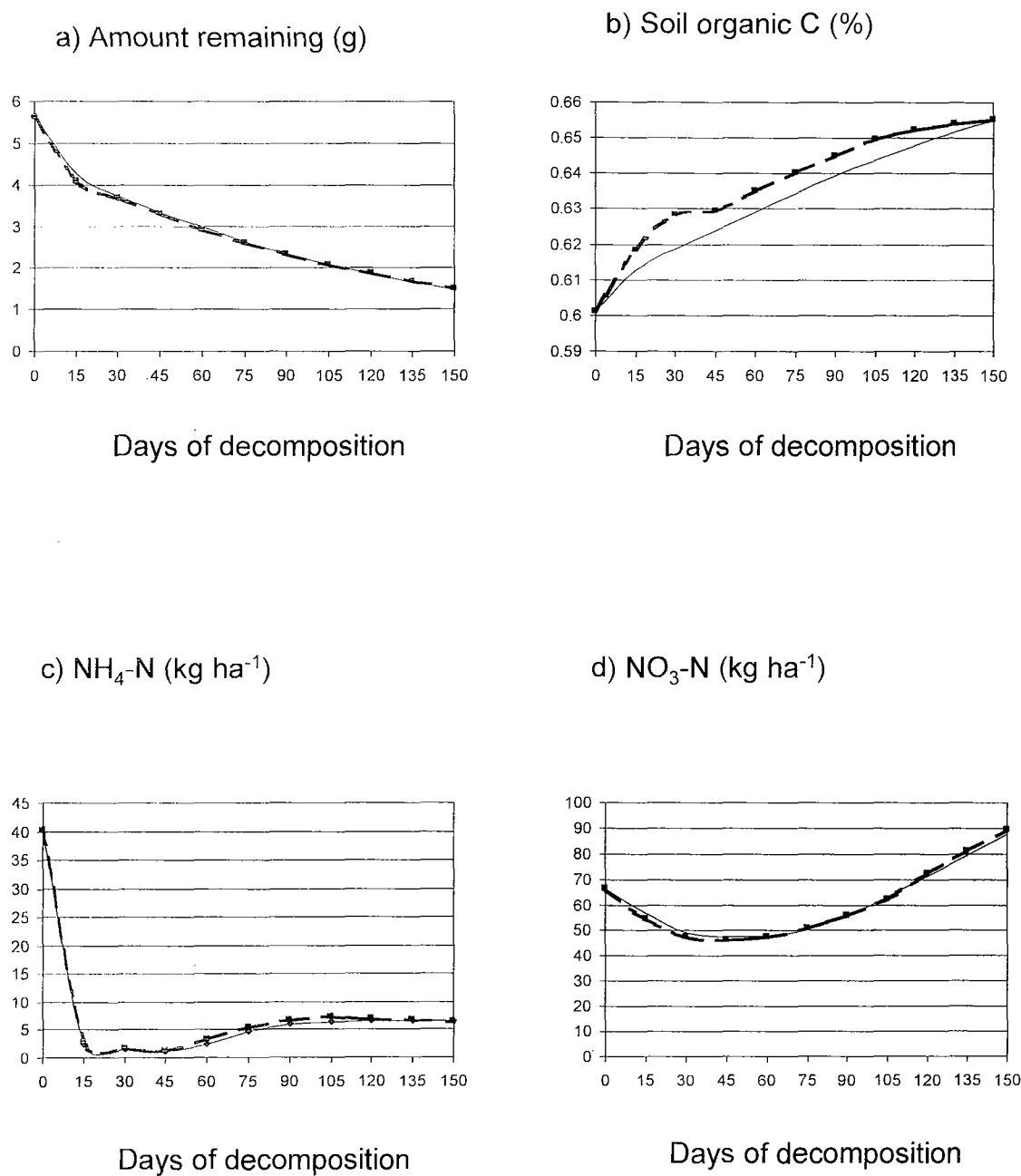
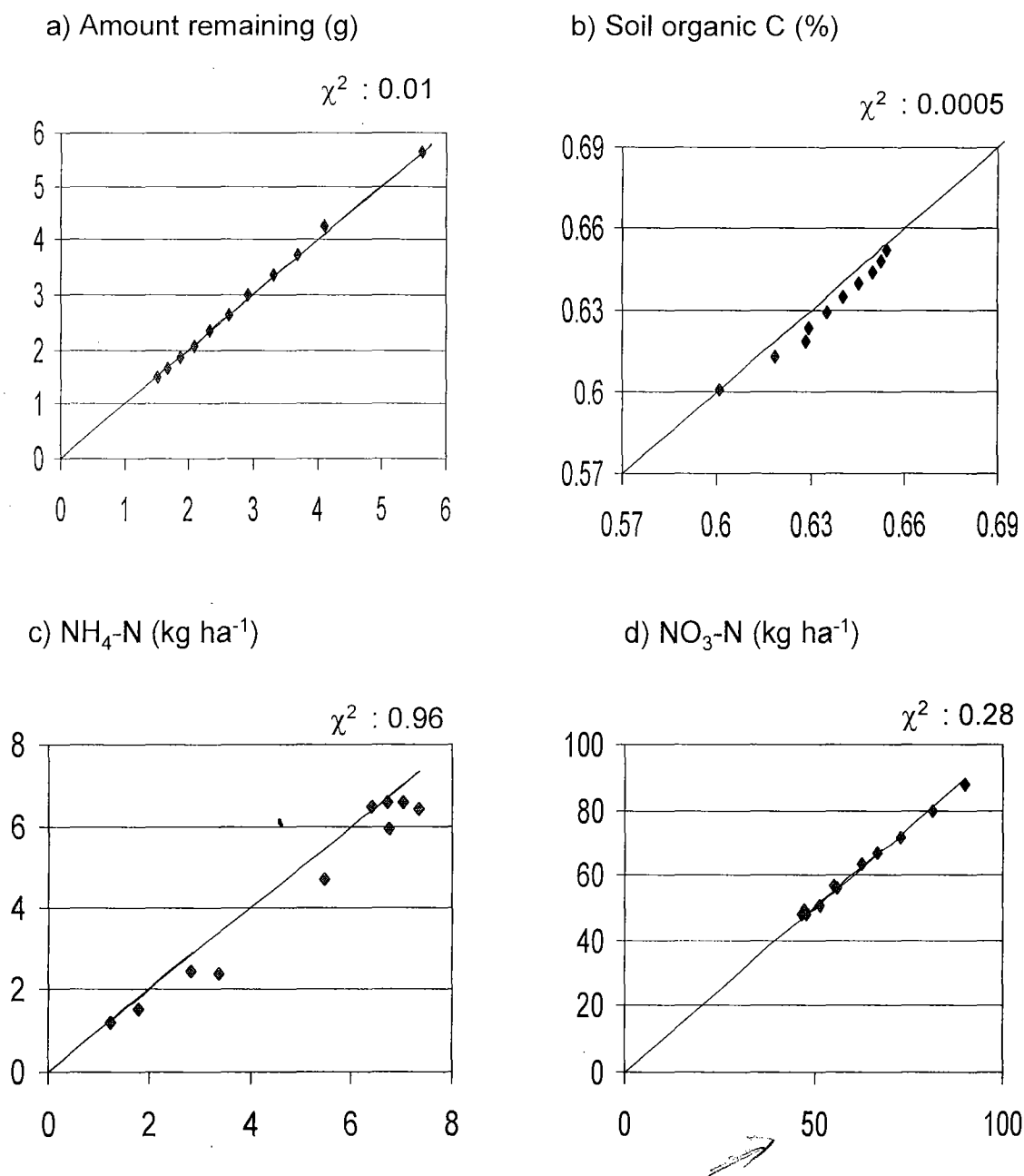


Fig. 120. Goodness of fit of observed (x-axis) and predicted (y-axis) values of different parameters associated with the decomposition of ambient CO₂-grown wheat residues (WA) under ambient atmospheric CO₂ condition



Amount of WA remaining inside the litterbags at different times of sampling during decomposition was found to follow a decreasing trend in its predicted as well as observed set of values. The decrease was sharp initially and the slope eased out towards the end of decomposition. The two sets of data had a χ^2 value of 0.01, which is higher than the corresponding χ^2 values for RA and RE. In other words, this means that the goodness of fit of the predicted values with the observed one was better in case of rice residues than in case of wheat residues.

During decomposition, the predicted and observed values of soil organic carbon were found to get increased with time (Fig. 119b). The model was found effective in predicting carbon release into soil during decomposition of WA with a χ^2 value of 0.0006 for this parameter (Fig. 120b).

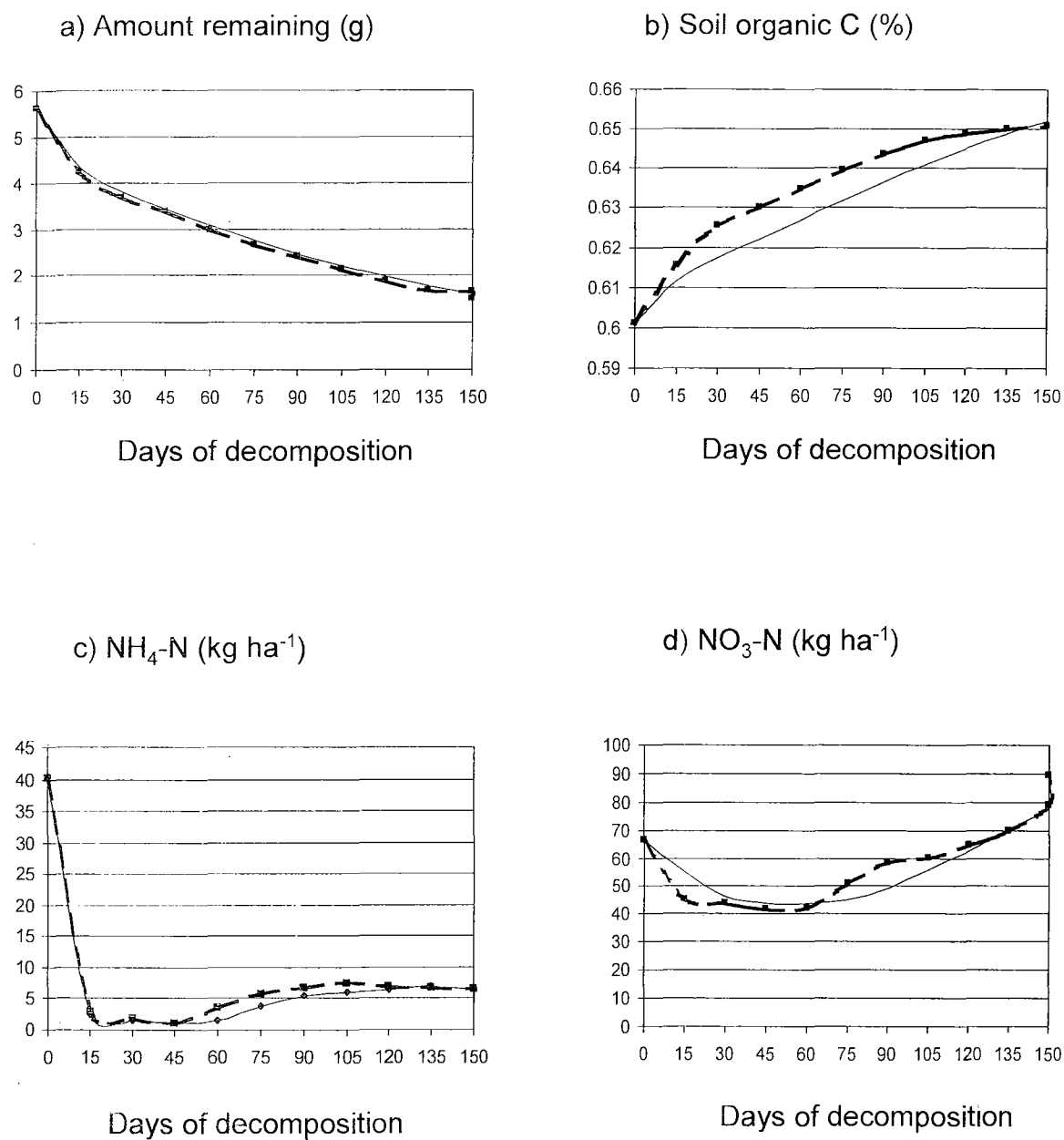
Ammoniacal nitrogen decreased initially and then increased, and towards the end of decomposition a slight decrease was again recorded (Fig. 119c). The trend was similar in both predicted and observed sets of values, and the model performance had a χ^2 value of 0.96 (Fig. 120c). Nitrate nitrogen was also found to get decreased from its initial contents indicating primary phase of immobilization followed by net mineralization. This trend was followed as such by the observed as well as predicted sets of data (fig. 119d), and the χ^2 value (0.27) was lesser than that of ammoniacal nitrogen (Fig. 120d).

4.4.5 CERES simulation of decomposition of WE

Lastly the model was evaluated for its ability to simulate carbon and nitrogen release during decomposition of WE. The modified values of decay parameters for CARB, CELL and LIGN were 0.29, 0.01508 and 0.0011, respectively. Input values for the model are given in Table 54. When these input values were fed to the modified model, the predicted values of the amount of the residue remaining inside the litterbags and the soil organic carbon were found to lie very closely to the observed values. However, the predicted and observed values of ammoniacal and nitrate nitrogen did not exhibit a very close relationship. *As per the figure*

Observed and predicted values of weight of the residue remaining inside the litterbags, soil organic carbon, ammoniacal and nitrate nitrogen in

Fig. 121. The predicted (solid line) and observed (dotted line) values of different parameters associated with the decomposition of elevated CO₂-grown wheat residues (WE) under elevated atmospheric CO₂ condition



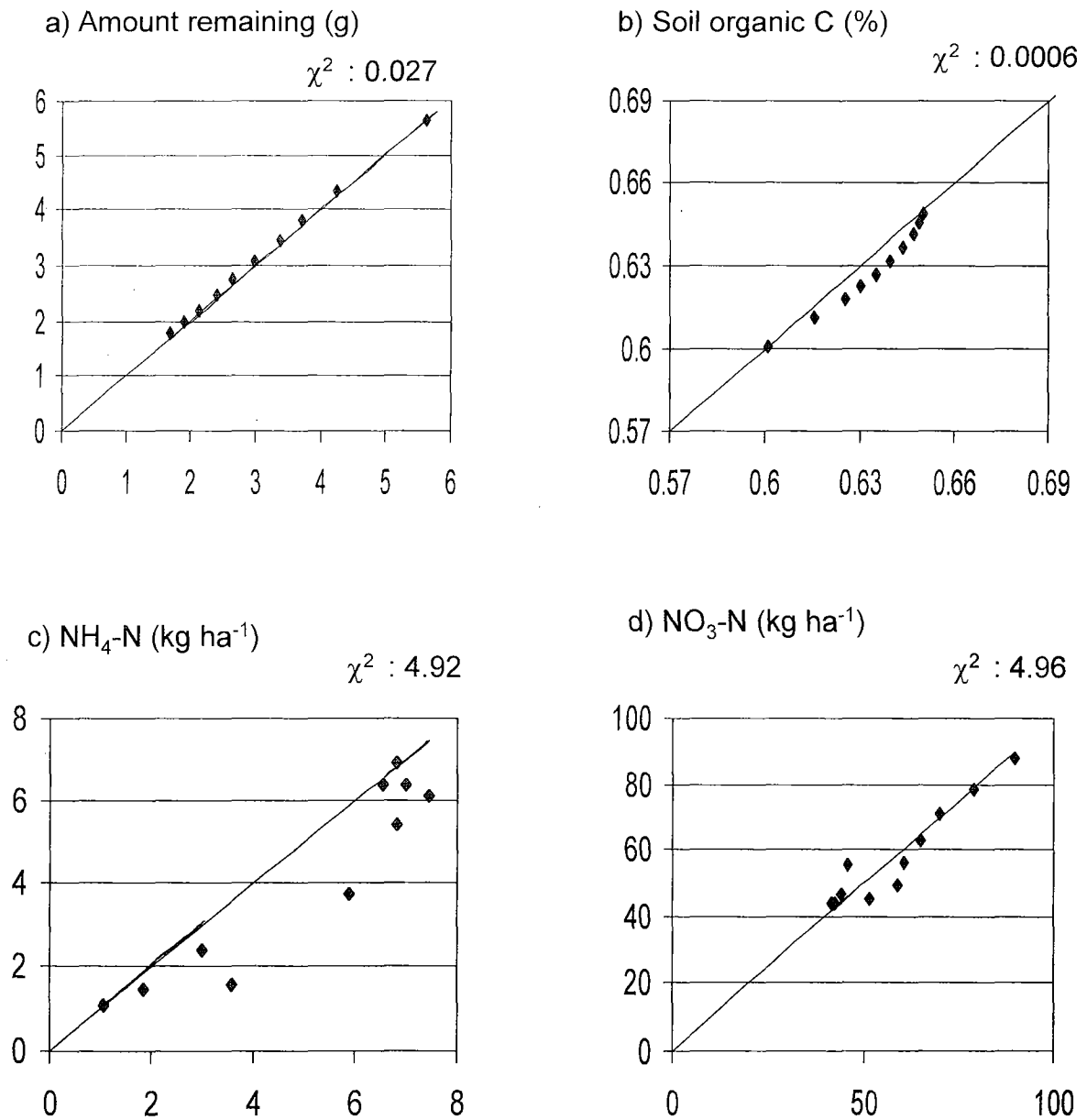
soil during decomposition of WE are shown in Figure 121 and 1:1 plots of observed vs predicted values are presented in Figure 122.

Amount of residue remaining inside the nylon bags declined sharply during initial period of decomposition of WE as well (Fig. 121a). This was true in case of predicted values also. The goodness of fit between observed and predicted values showed a clear harmony between the two sets of values, with χ^2 value of 0.027 (Fig. 122a).

In case of total organic carbon in soil, the observed and predicted values exhibited an increasing trend like all other cases. The data was found to fit well to the model with a χ^2 value of 0.0006 (Fig. 122b). The lower χ^2 values specified the effectiveness of CERES-N to simulate the C mineralization during the decomposition of WE.

Nitrate and ammoniacal nitrogen in soil did not exhibit perfect accordance between the observed and predicted values associated with the decomposition of WA. As discussed in the previous section, the ammoniacal nitrogen decreased from an initial value of 40.3 kg ha⁻¹ during initial period of decomposition of the residue, later increased and then decreased slightly. The predicted values of ammoniacal nitrogen followed this trend. However, the observed values deviated much from the predicted values and in general the observed values were higher than the predicted values. Nitrate nitrogen contents followed the trend of initial decrease and subsequent increase both in case of observed and predicted values, indicating immobilization and mineralization occurring in succession. However, the χ^2 value recorded in the observed vs predicted plots were as high as 4.92 and 4.96 for the ammoniacal and nitrate nitrogen pools in soil, respectively. The values were higher compared to those associated with the parameters of amount of residue remaining and soil organic carbon (Fig. 122c and d). The χ^2 values were higher in comparison to the corresponding values associated with RA, RE or WA as well. However, the values were lower than the corresponding Table values. This implies that the model can simulate N mineralization during decomposition of WE to a lesser degree compared to other parameters.

Fig. 122. Goodness of fit of observed (x-axis) and predicted (y-axis) values of different parameters associated with the decomposition of elevated CO₂-grown wheat residues (WE) under elevated atmospheric CO₂ condition



C₃ plants compared to C₄ plants. When exposed to ambient + 320 ppm CO₂, a doubling of yield in wheat was reported by Paterson and coworkers (1996).

The positive response in rice and wheat growth can be explained in terms of the higher CO₂ compensation point too. The CO₂ concentration at which the CO₂ released from leaves by respiration and photorespiration exactly balance with photosynthetic CO₂ assimilation is known as CO₂ compensation point. The CO₂ compensation point is an indicator of the capacity of the plant to absorb CO₂ from environment and to assimilate it efficiently in light. The lower the compensation point, the better will be the CO₂ photo-assimilation capacity. It is very low (<10 ppm) for the C₄ plants whereas, for the C₃ species the values exceed 50 ppm measured at 25°C in saturating light. Thus C₃ crops can exhibit an increase in photo-assimilation capacity with elevation of atmospheric CO₂ concentration, as long as the CO₂ compensation point is not reached. This explains the increase in the biomass yield of rice and wheat in response to the elevation of atmospheric CO₂ concentration. By analyzing many results, Kimball (1986) came to a general conclusion that a doubling of CO₂ increases the photosynthetic rate by 30 per cent; depending on other environmental conditions. Growth and yield is altogether a balance between photosynthetic gain and loss of carbohydrate by respiration. Cure in 1985, analyzing the results of eight studies commented that the average effect of doubled CO₂ concentration on wheat yield is an increase by 35 per cent. The results of the current pot culture study stand exactly in this range.

Compared among different plant parts in wheat, root dry matter and in rice, grains experienced highest per cent gains in response to the elevation of atmospheric CO₂ concentration. The respective gains under elevated CO₂ in root, leaf, stem and grain yields were by 34.95, 43.97, 18.80 and 48.11 per cents in rice and 70.54, 42.50, 21.00 and 35.39 per cents in wheat, respectively. Yield-stimulations obtained in the current study were higher than the mean biomass stimulations, and therefore caused improvements in harvest index (HI). A better improvement in HI was observed in case of rice as the response to grain weight was high. Such differential response between shoots and tubers representing reallocation of resources under high CO₂ to

improve harvest index (HI) has been reported by Miglietta and co-workers (1998). In their experiment, tuber yields from potato increased by 28 per cent due to elevation of CO₂, which stands in marked contrast to the average 21 per cent decrease in biomass of the shoots.

Many researchers have observed preferential accumulation of biomass in roots. In the current investigation, root dry matter yield of wheat was increased by 70.54 per cent which amounts very high in comparison to the average of 33.83 per cent increase in total biomass. Data related to root dry weight, fresh root weight as well as root volume obtained from the current pot culture study corroborated such trend of increased partitioning of assimilates belowground. Nevertheless, the underground partitioning of biomass was not that much evident in rice. Kimball (1986) in his review, analyzing many results, commented that root growth of C₃ grasses was simulated by about 47 per cent on an average by elevation of CO₂ under conditions of ample water and nutrients, which is substantially greater than the average 12 per cent for the shoots. In the present investigation, at all four stages of growth in rice and wheat, the per cent biomass allocation belowground to root was higher under elevated CO₂. Rogers and coworkers (1994) found that root dry weight increased under elevated CO₂ in most investigations regardless of the species or study conditions. In many other instances also, roots exhibited the greatest relative dry weight gain among plant organs under high CO₂ (Hocking and Meyer, 1991., Norby *et al.*, 1999). These studies support results of current investigation that reiterated the increased partitioning of biomass towards root.

Carbon accumulation and distribution also showed the increase in root:shoot ratio under elevated CO₂. At all stages of crop growth, exposure to higher CO₂ in atmosphere increased the preferential partitioning of carbon to roots both in rice and wheat. A similar increased belowground partitioning of C was observed by Griffith and coworkers (1998) and they ascribed it to the increased non-microbial biomass residue in rhizosphere. Similar increases in long term partitioning of assimilates to the roots due to elevated CO₂ have been reported for a wide range of herbaceous species; for example, *Abutilon theophrasti* (Patterson and Flint, 1980), *Brassica juncea* (Kriedman and

Wong, 1984), *Carex bigelowii* (Oberbauer *et al.*, 1986) and *Glycine max* (Patterson and Flint, 1980). However Cure and Acock (1986) commented that cereals often do not show long term changes in the partitioning of assimilate between root and shoot in response to increased CO₂. However, the results of the current investigation stand in contrary to such comments. There are other reports too. Billes and coworkers (1993) reported an increase in root:shoot ratio by 3 per cent in *Triticum aestivum*, when no nitrogen was added to soil. Du Loux and coworkers (1987) recorded an increase by 60.8 per cent in root:shoot ratio of wheat as a result of elevation of atmospheric CO₂ concentration while, Masle and coworkers (1990) reported CO₂-stimulated increases in R:S ratios of wheat in loose and compact soil by 13.3 and 22.7 per cent; while, Wong and Osmond (1991) recorded an increase by 56.5 per cent when wheat was grown in greenhouse.

A reduction in N concentration in different parts of rice and wheat was observed. Similar reduction has been reported in different crop species (Hocking and Meyer, 1991; Conroy, 1992; Rogers *et al.*, 1996; Ziska *et al.*, 1996). Rogers and coworkers suggested that the reduction in N may be due to dilution effect as a result of greater carbohydrate accumulation, while Coleman and associates (1993) explained the reduction as due to the acceleration of plant growth, and not due to increased NUE (Coleman *et al.*, 1993). Acceleration of growth as well as increased carbohydrate accumulation (indicated by the absence of dilution effect in case of C concentration) has been recorded in the present study also. Hence these might have led to the decreased N composition of elevated CO₂-grown plants. However the decrease in N contents was not that prominent incase of wheat.

4.5.2 Carbon pools in soil

The increase in root to shoot biomass ratio and preferential partitioning of biomass and carbon belowground has considerable impacts on carbon dynamics in soil. Root turnover is one of the most important mechanisms of carbon transfer to the rhizosphere soil (Van Veen *et al.*, 1991). Gorrissen (1996) found that regardless of the total biomass response to elevated CO₂, total net ¹⁴C-CO₂ uptake increased by an average of 41 per cent and the carbon transferred to root and to the soil increased by 31 and 35 per cent,

respectively, in elevated CO₂ treatments over the ambient ones. Although a relatively minor pathway for transferring carbon to soils, the nature of exudates may be more important for ecosystem than their overall quantity (Cardon, 1996). An increase in root growth as well as belowground partitioning had been observed in the present experiment and this might have certain implications on the carbon pools in soil.

Hence, active carbon pools in the rhizospheres of crops might be considered as reflections of the response of the above and belowground biomasses towards elevation of atmospheric CO₂ concentration. The regression analysis conducted during investigation further strengthens the relationship between the two. Total C uptake, biomass partitioning and root composition were found to contribute to the variability in the values of different fractions of carbon and nitrogen. Elevated CO₂ might lead to increased root exudation into soils, which in turn, might impart influence on microbial activity, community composition, degradation of soil organic matter and consequent availability of nutrients to plants.

Helal and Sauerbeck (1986) showed that growing root is an important carbon source for microbial biomass. Zak and coworkers (1993) hypothesized that greater soil carbon availability under elevated CO₂ could elicit an increased size of soil microbial biomass. Results of the current study revealed that all the active carbon pools were influenced positively by the elevation of atmospheric CO₂ concentration. It was hypothesized that increased root growth and consequent increased microbial activity under elevated CO₂ would have caused such influence on these pools. Results emanating from the pot culture as well as field experiments (using FACE technology) supported this hypothesis. However, relative advantages were of different order and magnitude in the rhizosphere soils of the two crops studied.

In the rhizosphere soil of rice, the relative extent of increase among the active carbon pools to elevated CO₂ were in the order of: MBC > DOC > CHC > LBC. This trend was clearly followed in both OTC and FACE. The respective gains in these pools when crop was taken in pots inside OTCs

were 40.70, 17.43, 9.079 and 6.8 per cents, and when grown under FACE, the respective gains were 18.91, 15.35, 8.04 and 7.43 per cents.

As plant production regulates the magnitude of C input to the soil and because microbial populations in soil are often limited by C (substrate) availability (Smith and Paul, 1990), increases in belowground carbon allocation in response to atmospheric CO₂ are expected to elicit a concomitant increase in microbial biomass. Anderson and Domsch (1986) argued that although soil microorganisms are limited by physical factors, microbial biomass is correlated to soil C content over a wide range of conditions. Insam and associates (1989) supported this view. Thomas and Strain (1991) suggested that at elevated CO₂, the extent to which C availability and microbial populations increase is dependent on the sink strength of fine roots for photosynthates. Hence the increased MBC in soil under elevated CO₂ can be ascribed to the increased allocation of C belowground observed in the present experiment. Zak and coworkers (1993) also reported higher MBC in rhizosphere and bulk soils of crops when grown under elevated atmospheric CO₂ concentration. In their study on rhizosphere soil, MBC in elevated CO₂ treatment was approximately 1.5 times greater than that in ambient treatment. However, we could not obtain that much increase in MBC under field condition.

In wheat rhizosphere, DOC experienced maximum increase among all the C pools, recording 17.41 per cent in response to elevation of atmospheric CO₂ concentration. It was followed by MBC (16.59), CHC (7.89) and LBC (7.55) in sequence, in the pot culture study. FACE experiment also produced the same order of gain in active carbon pools, but differed slightly in their absolute values. Relative extent of increase in these parameters under field condition were: DOC (17.91) > MBC (17.30) > CHC (8.88) > LBC (8.38). Zak and coworkers (1993) reported an increase in labile carbon pool under elevated CO₂.

When soil samples were collected from different depths of FACE field and analyzed, the relative gains in various active carbon pools on exposure to elevated CO₂ were found to decline sharply as the depth of sampling increased. This clearly indicated that the relative advantage of elevation of

CO₂ is restricted to the upper layers of soil. This fact reiterated the importance of rhizosphere effect in terms of root exudations, that is restricted to the upper layers of soil. When rice crop was grown under FACE, the per cent responses of active carbon pools to elevation of atmospheric CO₂ concentration was higher in 0-5 cm layer of soil. In case of wheat crop, the gains in the pools were higher in 5-10 centimeter layer of soil, excepting DOC where both 0-5 and 5-10 cm depths behaved similarly. As rice is a wetland crop the positive effect of elevated CO₂ is expected to be maximum in the upper soil layer (relatively more oxidized) while in case of wheat, the direct exposure of surface soil to atmosphere (primarily heat) might cause subsurface (5-10 cm) area to be more congenial for microbial activity.

In both rice and wheat, values of different active carbon pools got altered with age of the crop. DOC decreased as the crops matured. The higher values of DOC during the initial phase of growth could be ascribed to the decomposition of the added residues in soil (wheat or rice straw) and partially to the exudation of low molecular weight substances from the younger root cells devoid of secondary cell wall.

Labile as well as carbohydrate carbon pools in rhizosphere soil were found to get increased as crops matured. Such increase in their values can be credited to the lysis of root tissues occurring towards maturity. MBC was highest at flowering (at the end of vegetative stage) and it decreased as the reproductive stage set in.

The total carbon contents in soil, primarily contributed by recalcitrant fraction, did not differ significantly in OTC (pot culture study) due to the elevation of atmospheric CO₂ concentration. But in field experiment, a small but significant increase in total soil carbon content was observed on exposure to elevated CO₂. Soil in FACE field had been exposed to higher CO₂ for the past seven years. This long-term exposure to CO₂ with crop stand might have increased the recalcitrant soil carbon pools as well. However, such increase was found to be significant only in the upper two layers of soil (0-10 cm) studied. Prior and coworkers (1997) also analyzed the recalcitrant carbon contents in different layers of soil (0-5, 5-10 and 10-20 cm from surface) and they reported an increase in organic carbon content at all the depths in FACE.

In our study, the positive effect of elevation of atmospheric CO₂ on TSC was restricted to the upper 0-5 cm soil layer in rice and 0-10 cm soil layer in wheat field.

Irrespective of the crop and CO₂ enrichment technology, the response obtained in different C pools followed the order of relative lability of the pools. The MBC and DOC represent the most labile pools among the four studied, and hence, these pools experienced maximum gain on exposure of the crops to elevated CO₂. However, the changes in these pools are not expected to contribute to the process of carbon sequestration significantly. Both the fractions of CHC and LBC contribute about 20 per cent of total soil carbon (TSC). As they are relatively labile in comparison to humic fraction, they are not included in the recalcitrant fraction of soil organic matter. But, they are comparatively more resistant than the two other pools (MBC and DOC). The LBC is even more resistant than CHC fraction. Hence a change in these pools can probably impart a small to medium term effect on C sequestration, as has been proved in the field experiment. The increase in TSC content observed in the field experiment can thus be ascribed to the cumulative effect of the gain in these labile pools of carbon over a long period.

4.5.3 Decomposition kinetics of ambient CO₂- and elevated CO₂-grown rice and wheat residues

Decomposition of plant residue added to soil is an important component in the turnover of organic carbon. The carbon fixed within the plant enters the soil *via* plant residues and may reside there for hundreds of years (Parton *et al.*, 1986). The effects of elevated CO₂ on aboveground physiological processes have been well documented. However, to date, soil ecosystems have received much less attention. The long-term capacity of soil to store carbon from CO₂ enrichment has not yet been determined (Houghton *et al.*, 1995) and many uncertainties remain regarding the extent to which increased C fixation under elevated CO₂ will alter the degradability of plant material.

The current investigation in phytotron chambers showed a decrease in degradability of the elevated CO₂-grown rice and wheat residues compared to those grown under ambient atmospheric CO₂ concentration. However the

decrease was more prominent with rice residues. There are many views by different scientists regarding the degradability of the elevated CO₂-grown residues. One possibility is that increased soil microbial activity due to additional carbon entering the soil in an elevated CO₂ environment (priming effect) would lead to increased decomposition of soil organic matter (Lekkerkerk *et al.*, 1990). Alternatively, increased C:N and lignin:N ratios of plant residue were reported in elevated CO₂-grown systems, predicting decreased rate of degradation of the residues. The latter hypothesis receives support from the results obtained in the current investigation.

The decomposition was studied for 150 days, after which plant carbon got reduced to 17.06, 20.61, 24.67 and 27.17 per cent of the initial value in RA, RE, WA and WE, respectively. The rate constants obtained by fitting the curves were 0.0704 and 0.0641 for RA and RE, respectively. Thus elevation of atmospheric CO₂ had reduced the degradation rate of rice residues by 8.85 per cent. In case of wheat residues, increased CO₂ concentration reduced the rate constant by 4.42 per cent. Rice residues were found to decompose at a faster rate than the wheat residues. The experiment conducted by Cotrufo and coworkers (1994) reported results similar to the outcome of the current study. In their experiment, Birch litter decomposition was markedly reduced for litter derived from high CO₂ treatment, with a value of WTREM (per cent weight remaining) 1/3 higher than for control. But a significant difference was observed between the ambient and elevated CO₂-grown Spruce litters with an increase in WTREM being associated with the elevated treatment. Hirshel and coworkers (1997) showed that decomposition of a sedge (*Carex curvula*) produced under elevated CO₂ was significantly slower than that of litter produced under ambient CO₂ (14 and 21% of the initial litter mass of ambient and elevated residues had decomposed over a 61 day exposure period). Such decreased rate of decomposition of elevated CO₂-grown residues were also observed in case of rice and wheat straw studied in the current investigation.

Substrate quality has been recognized as one of the most important factors regulating decomposition processes (Swift *et al.*, 1979). Quality parameters such as nitrogen concentration, C:N and lignin:N ratios have been

correlated with decomposition rates (Melillo *et al.*, 1982., Taylor *et al.*, 1989). The effect of increasing CO₂ levels on plant material quality has been the subject of many studies. In general, a reduction of N concentration with a concomitant increase in C:N ratio is likely to occur (Coleman *et al.*, 1993). A similar trend of reduction in N concentration and concomitant increase in C:N ratio in elevated CO₂-grown residues was observed in the current investigation. Bazzaz and Miao (1993) reported that the responses of plants to elevated CO₂ are species dependent. The effect of elevated CO₂ concentration, manifested in terms of reduction in N concentration was less pronounced in case of wheat when compared to rice residues. A decrease of N concentration by 4.08 per cent was observed in wheat residues as a result of elevation of atmospheric CO₂, while the corresponding decrease was by 5.09 per cent in rice residues. Nevertheless, the changes in N concentration and C/N ratio in both the residues might have got specific effects on the rate of decomposition of the residues. The decrease in per cent N composition might have resulted in the decrease in the decomposability of the elevated CO₂-grown residues. The decreases in decomposability of the residues were evident from the weight and carbon concentration of the residue remaining inside the litterbags during decomposition.

The hypothesis that rising atmospheric CO₂ concentration will reduce litter quality and its degradability has been proved from the present study. It is further assumed that such reductions will lead to decreased rates of nutrient cycling and dampen the potential CO₂ stimulation of carbon sequestration in native ecosystems (Rastetter *et al.*, 1992). In the present study, elevated CO₂-grown residues were found to be associated with lower soil carbon contents during decomposition when compared to the ambient CO₂-grown residues. However difference of soil carbon during the decomposition of elevated CO₂-grown and ambient CO₂-grown residues was less in wheat compared to rice. This trend is in conformity with the observed change in degradability of the residues. A decrease in the rate of mineralisation has been observed during the decomposition of elevated CO₂-grown both rice and wheat residues.

Overall, the results indicated a small but definite decrease in decomposability of residues when they are grown under elevated atmospheric

CO₂ conditions. This was in accordance with the changes in litter quality parameters observed under elevated vis-à-vis ambient atmospheric CO₂ conditions.

4.5.4 Modifications done for CERES-N to simulate the decomposition and mineralization from the residues

The CERES-N model was modified for simulating the decomposition of ambient and elevated CO₂-grown rice and wheat residues using the data obtained from the decomposition study. In the original CERES model the rate constants of decomposition for carbohydrate, cellulose and lignin pools were proposed by Godwin and Jones in 1991. Later, many validation studies have been done which has proposed modified decay parameters for these pools. In 1991, Vigil and coworkers modified the decay constants of CARB, CELL and LIGN as 0.05, 0.0045 and 0.00095 day⁻¹, respectively. Bowen and coworkers (1993) also validated the model and the modified decay constants obtained by fitting their observed data to the model were: 0.2, 0.05 and 0.0095 and 0.14, 0.0034 and 0.0095 day⁻¹ for CARB, CELL and LIGN, respectively. In the current experiment, initially, the rate constants proposed by Bowen and coworkers (1993) were used. However, when these values were fed, the output values deviated a lot from the observed results. Hence, modifications of these parameters were carried out through repeated runs of the model to bring high degree of goodness of fit between the observed and the predicted values. Thus, the current experimental results modified the decay parameters (decay constants for CARB, CELL and LIGN obtained through iterative method) into four sets of values for the four different types of residues. The modified decay constants for carbohydrate, cellulose and lignin were 0.38, 0.01899 and 0.0035 in case of RA. The respective values were 0.32, 0.01691 and 0.00266 for RE, 0.31, 0.01561 and 0.0013 for WA and 0.29, 0.01508 and 0.0011 for WE. When Quemada and coworkers (1997) evaluated the ability of the model to predict nitrogen release from surface applied cover crop residues, the best fitting rate constants obtained were 0.67 and 0.021 day⁻¹ for CARB and CELL, respectively. The fitted rate constants for CERES-N with user supplied pool sizes were larger than the values of CARB and CELL

5. SUMMARY AND CONCLUSIONS

One of the major challenges of modern ecological research is to understand how the biosphere is responding to human-induced global environmental changes. One of such global changes is the rapid rate of increase in atmospheric CO₂ concentration since pre-industrial times, currently amounting to 370 ppm. Terrestrial ecosystem structure and function is highly dependent on the relationship between plants and soil systems. Increasing CO₂ levels typically lead to significant increases in photosynthetic rates, and can lead to changes in the growth of whole plants and plant community structure. Recently, there has been much interest in determining the capacity of sequestering carbon from the atmosphere. If terrestrial vegetation responds to increasing CO₂ levels with increased net primary production leading to storage of carbon, then terrestrial vegetation might play a significant role in preventing the effects of global warming, though to a limited extent. Another possibility is that CO₂ enrichment might alter the quality of organic matter, thereby indirectly affect the rate at which carbon and nitrogen are cycled within the soil plant system. The effects of elevated CO₂ on aboveground physiological processes have been well studied. However, to date, soil ecosystems have received much less attention.

To study the impacts of elevation of CO₂ on soil system, a pot culture experiment (rice-wheat sequence), a field experiment (rice-wheat sequence) and a decomposition study (rice and wheat residues) were undertaken. The pot culture experiment was conducted in open top chambers (OTCs) with surface soils collected from a Typic Haplustept (IARI, New Delhi). Rice and wheat were grown as test crops at ambient (approx. 370 $\mu\text{mol mol}^{-1}$) and elevated (600 $\pm$ 50 $\mu\text{mol mol}^{-1}$) levels of atmospheric CO₂. Wheat and rice residues grown at elevated CO₂ were incorporated in soil at the rate of 9 g kg⁻¹ soil in rice and wheat crops, respectively, under elevated CO₂ conditions,

and the ambient CO₂-grown rice and wheat residues were incorporated in crops grown under ambient CO₂. Destructive sampling was done at four physiological stages of crop growth namely tillering (rice) /crown root initiation (wheat), anthesis, grain filling and maturity. Biomass yield, carbon content and its uptake by different plant parts (*viz.* root, stem, leaf and grain) and various carbon fractions in rhizosphere soil, namely, microbial biomass carbon (MBC), dissolved organic carbon (DOC), carbohydrate carbon (CHC), labile carbon (LBC) as well as total soil carbon (TSC) were determined for both the crops at each of the crop growth stages.

Rice and wheat crops were grown in field also under free air carbon dioxide enrichment (FACE) and ambient CO₂ conditions. Soil samples were collected from four depths (0-5, 5-10, 10-15 and 15-20 cms) and analyzed for the same parameters (MBC, DOC, CHC, LBC and TSC).

The crop residue decomposition study was conducted in phytotron chambers of National Phytotron Facility, IARI, New Delhi. The litterbags with ambient and elevated CO₂-grown rice and wheat residues were inserted into soil in pots, which were arranged in racks inside the phytotron chambers maintained at respective CO₂ levels. After every fifteen days destructive sampling of the pots along with litterbags was done, and the decomposition was then continued for 5 months. The collected soil samples and plant residues remaining inside the litterbags were analyzed for different parameters. Soil samples were analyzed for total organic carbon, microbial biomass carbon, ammoniacal and nitrate nitrogen, while left over in litterbags were analyzed for carbon and nitrogen contents. The rates of decomposition of elevated and ambient CO₂ grown residues were computed from the data related to kinetics of decomposition and comparisons were made.

The data generated was used to evaluate the ability of CERES-N model to simulate carbon and nitrogen mineralisation from rice and wheat residues grown under ambient and elevated CO₂ concentrations. The model could predict these processes after certain modifications (obtained through repeated runs of the model) were made.

Main findings from these sets of experiments are listed in this chapter.

Plant biomass yield and its partitioning

The data related to plant parameters ~~is~~ derived solely from the pot culture (OTC) experiment:

- Total biomass yield was increased by 32.26 and 32.98 per cents as a result of elevation of CO₂ concentration in the micro climate of rice and wheat, respectively.
- Various plant parts differed with respect to their relative gain in yield, and the order varied in the two test crops. The relative gains in biomass of different plant parts on exposure to elevated CO₂ were in the order of:
 Rice: Grain (48.11) > Leaves (43.97) > roots (34.95) > stem (18.80)
 Wheat: Root (70.54) > Leaves (42.50) > grain (35.39) > stem (21.00).
- The fresh root weight was increased by 35.31 and 73.01 per cents, respectively, for rice and wheat, as a consequence of the elevation of CO₂ concentration in atmosphere.
- The root volume was also increased by 36.56 and 77.13 per cents in rice and wheat, respectively under elevated CO₂.
- The data on biomass partitioning indicated a higher rate of translocation of the dry matter towards root at all stages of growth in both rice and wheat. However the below ground partitioning was comparatively more in wheat crop.
- The carbon uptake by both rice and wheat were increased by the increased concentration of CO₂ in atmosphere.
- The per cent carbon content of different plant parts did not differ significantly excepting the root dry matter of rice, which exhibited a small but statistically significant increase in its carbon content under elevated CO₂.
- The respective increases (per cent) in carbon uptake by different plant parts of the crops were in the order of:
 Rice: Root (44.81) > Leaves (42.64) > grain (39.51) > stem (20.09)
 Wheat: Root (70.21) > Leaves (42.51) > grain (38.32) > stem (22.09).
- Total C uptake by rice was increased by 33.83 per cent, while in wheat an increase of 33.25 per cent was recorded.

- As the gains in the economic parts were relatively higher when compared to the gains in total biomass yield, an improvement in harvest index was obtained under elevated CO₂ in both rice and wheat, enhancement being more prominent in rice crop.
- As a result of elevation of CO₂ concentration in atmosphere during rice growth, per cent carbon allocated below ground increased from 37.62 to 43.30 per cent at tillering, while the corresponding increases were from 25.12 to 27.47, 19.78 to 21.43 and 15.60 to 17.15 per cents at flowering, grain filling and maturity, respectively.
- As a consequence of higher CO₂ concentration in atmosphere, per cent carbon allocated below ground increased from 26.29 to 30.94 per cent at CRI stage of wheat growth, while the corresponding increases at anthesis, grain filling and maturity were from 13.10 to 16.26, 9.21 to 13.74 and 4.07 to 4.30 per cents, respectively.
- Per cent nitrogen content of different plant parts were slightly lower under elevated CO₂ conditions and this effect was more prominent in the case of rice.
- The lower nitrogen content resulted in higher values of C:N ratio for all plant parts when rice was grown under elevated CO₂.
- Though comparatively small, the C:N ratios of wheat plant parts were also increased as a result of elevation of CO₂ concentration in atmosphere.

Gains in carbon pools of rhizosphere soil

These results were obtained from the analysis of the soil samples collected from pot culture (OTC) as well as field experiments (FACE):

- The results of pot culture and field experiment indicated that microbial biomass carbon (MBC) content in soil was positively affected by elevation atmospheric CO₂ concentration. The respective gains were 40.7 and ~~17.41~~^{16.59} per cent in rice and wheat rhizosphere soils, respectively during pot culture experiment. The corresponding increases for the two crops were 18.91 and 17.30 in field experiment.
- All active carbon fractions in soil increased as a result of the increased atmospheric CO₂ concentration.

- The specific gains in these carbon pools on exposure of the crops to increased CO₂ concentration were in the order of:

Pot culture experiment

Rice: MBC (40.70) > DOC (17.43) > CHC (9.079) > LBC (6.8)

Wheat: DOC (17.41) > MBC (16.59) > CHC (7.89) > LBC (7.55)

Field experiment

Rice: MBC (18.91) > DOC (15.35) > CHC (8.04) > LBC (7.43)

Wheat: DOC (17.91) > MBC (17.30) > CHC (8.88) > LBC (8.38)

- The recalcitrant total soil carbon (TSC) content did not differ significantly in OTCs (pot culture study) in response to the elevation of atmospheric CO₂ concentration.
- Interestingly, in the field experiment a significant increase in total carbon contents in surface (0-10 cm) soil was observed under FACE. The soil in field under FACE has continuously been exposed to higher CO₂ for the past seven years. This long-term exposure to CO₂ with crop-stand might have increased the calcitrant carbon pool in soil.
- While CHC and LBC contents in rhizosphere soil increased towards maturity, DOC showed a declining trend with age of the crop.
- In general, MBC content was highest at flowering stage in both the crops and it further decreased on either sides of growth curve. An exception to this trend was observed in case of rice in pot culture experiment under ambient CO₂, wherein the highest value was observed at tillering stage, which further decreased as the crop proceeded towards maturity. Under elevated CO₂, tillering and flowering stages of rice did not differ significantly with respect to MBC contents in rhizosphere soil.
- All carbon pools in soil collected from field declined in their quantity down the soil profile.
- The relative gains in the active carbon pools on exposure to elevated CO₂ also declined with increase in soil depth. This clearly indicated that the relative advantage of elevation of CO₂ is restricted to the upper layers of soil, symptomatic of the importance of rhizosphere effect in terms of root exudations and turn over.

- When rice crop was grown, the per cent response in active carbon pools to elevation of atmospheric CO₂ concentration was highest in 0-5 cm soil layer, while in wheat, it was highest in 5-10 cm layer (with an exception in DOC content). The two topmost layers of soil did not differ with respect to the per cent response in DOC content during wheat growth.
- The respective gains in these carbon pools in soil at different depths when rice and wheat crops were grown in FACE are given below:

Rice

0-5 cm : MBC (30.91) > DOC (26.31) > CHC (11.28) > LBC (10.53)

5-10 cm : MBC (21.93) > DOC (20.68) > CHC (9.05) > LBC (8.83)

10- 15 cm : DOC (8.11) > MBC (7.57) > LBC (4.64) > CHC (4.05)

15- 20 cm : MBC (1.55) > DOC (0.72) > CHC (0.45) > LBC (0.19)

Wheat

0-5 cm : DOC (28.00) > MBC (21.74) > CHC (10.39) > LBC (9.81)

5-10 cm: DOC (27.54) > MBC (24.61) > LBC (12.65) > CHC (12.62)

10- 15 cm : MBC (10.18) > DOC (8.48) > CHC (4.31) > LBC (3.66)

15- 20 cm : DOC (5.33) > MBC (2.76) > CHC (1.14) > LBC (1.11)

- As a result of elevation of CO₂ concentration in rice microclimate, a decrease in NH₄-N content by 16.66 per cent was observed in rhizosphere soil during pot culture experiment while nitrate nitrogen did not exhibit any significant change in its values.
- As the level of CO₂ was increased in crop atmosphere, a decrease in NO₃-N content by 11.76 per cent was recorded in wheat rhizosphere soil while, ammoniacal nitrogen content was not affected significantly.

Decomposition Study

Ambient and elevated CO₂-grown rice and wheat residues were compared with respect to their degradability under ambient and elevated atmospheric CO₂ conditions, respectively.

Kinetics of decomposition of rice and wheat residues

- Ambient CO₂-grown rice (RA) and wheat (WA) residues were found to decompose at a faster rate compared to the corresponding elevated CO₂-grown residues (RE and WE).

- The amount of residues remaining inside the litterbags showed comparatively higher values for the elevated CO₂ grown residues indicating their slower rate of decomposition. The effect was more prominent for rice residue.
- The per cent carbon content of the left-over residues in litterbags at various times of sampling during decomposition did not differ significantly between the ambient and elevated CO₂ grown rice and wheat residues.
- After 150 days of decomposition, the weight of the residues and the amount of plant carbon inside the litterbags got decreased to 18.73 and 17.08 per cent of their initial values, respectively in case of ambient CO₂-grown rice residues (RA). The respective values for RE, WA and WE were 22.61 and 20.61, 26.90 and 24.67 & 29.50 and 27.17 per cents.
- The plot of logarithm *ie.*, expression of rate of residue carbon remaining in litterbags with time confirmed the slower rate of decomposition of elevated CO₂-grown residues.
- The slope of best-fitted straight lines representing this parameter was 0.0704 and 0.0641 for RA and RE, respectively, thus amounting to a decrease by 8.95 per cent in the rate of decomposition. In case of wheat residues the respective values for WA and WE were 0.0565 and 0.054, which meant a decrease of 4.42 per cent.
- The decreased rate of decomposition of elevated CO₂-grown residues were corroborated with the values of total organic carbon and microbial biomass carbon contents in soil. However, such difference between the values associated with ambient and elevated residues was higher for rice as the effect of elevation of CO₂ was more prominent during its decay.
- Ambient CO₂-grown residues had lower C:N ratios, as a result of which an increase was observed in its rate of minearlisation. Hence lower C:N ratios of RA and WA in comparison to RE and WE at all stages of decomposition, as obtained in the current study has enormous consequences in nitrogen cycling in soil.

Modelling experiment

- CERES-N with the original rate constants for carbohydrate (CARB), cellulose (CELL) and lignin (LIGN) pools overestimated the decomposition and mineralisation processes.
- The modified decay constants for carbohydrate, cellulose and lignin were 0.38, 0.01899 and 0.0035 in case of RA. The respective values were; 0.32, 0.01691 and 0.00266 for RE; 0.31, 0.01561 and 0.0013 for WA and 0.29, 0.01508 and 0.0011 for WE.
- A modification was done to include the proportional intake of ammoniacal nitrogen for immobilization. The limiting value of BB, nitrification factor was also changed from 0.8 to 0.6.
- The data related to the decomposition and N mineralisation from ambient and elevated CO₂-grown rice residues were found to fit quite closely to the modified CERES model.
- In case of wheat, the data pertaining to the decomposition from ambient and elevated CO₂-grown residues were found to fit well into the modified CERES model, while that related to N mineralisation from wheat residues did not fit well; especially in case of elevated CO₂-grown residues.

CONCLUSIONS

- Elevation of atmospheric CO₂ concentration brought an increase in all active carbon pools in crop rhizosphere; extent of gains were related to the relative lability of the active pools.
- Though marginal, significant increase in total soil carbon in upper layers of FACE indicates a definite possibility of increase in carbon sequestration arising out of the active pools on long-term exposure to elevated CO₂.
- Decomposition of crop residues was marginally faster in ambient CO₂ conditions and this effect was more prominent with rice residues. Such decreased rate of decomposition might increase the residence times of the elevated CO₂-grown residue decomposition systems, thus supplementing sequestration of carbon in soil.
- During decomposition of the residues, C:N ratios were lower for ambient CO₂-grown residues and that significantly increased the rate of minearlisation from those residues. Such alterations in C:N ratio have enormous consequences on nitrogen cycling in soil.

REFERENCES

- Abrol, Y.P., Bansal, A.K. and Mishra, R.S. (1996) Comparative study on the effect of elevated CO₂ in mungbean and maize cultivars. *Proceedings of the Indian National Science Academy*, **62**: 31-38.
- Agren, I.G., McMurtrie, R.E., Parton, W.J., Paster, J. and Shugart, H.H. (1991) State-of-the-art of models of production-decomposition linkages in conifer and grassland ecosystems. *Ecological Applications*, **1**: 118-138.
- Allen, L.H. Jr., Drake, B.G., Rogers, H.H. and Shinn, J.H. (1992) Field techniques for exposure of plants and ecosystems to elevated CO₂ and other trace gases. *Critical Reviews in Plant Science*, **11**(2-3): 85-119.
- Anderson, T.H. and Domesch, K.H. (1986) Carbon link between microbial biomass and soil organic matter. In: *Proceedings of the Fourth International Symposium on Microbial Ecology*. (Megusar, F. and Gantar, M. eds.), Slovene Society Microb., Ljubljana, Yugoslavia pp. 476-471.
- Angelis, P.D., Kesari, S., Chinwerewe and Mugnozsa, G.E.S. (2000) Litter quality and decomposition in a CO₂ enriched Mediterranean forest ecosystem. *Plant and Soil*, **224**: 31-41.
- Baker, J.T., Allen, L.H. and Boote, K.J. (1990) Growth and yield responses of rice to carbon dioxide concentration. *Journal of Agricultural Sciences*, **115**: 313-320.
- Ball, A.S. (1991) *FEMS Microbiology Letter*, **84**: 139-142.
- Battle, M., Bender, M. L. Tans, P.P., White, J.W.C., Ellis, J.T., Conway, T. and Francey, R.J. (2000) Global carbon sinks and their variability inferred from atmospheric O₂ and d¹³C, *Science*, **287**: 2467-2470.
- Bazzaz, F.A. (1990) The response of natural ecosystems to the rising global CO₂ levels. *Annual Review of Ecological Systems*, **21**: 167-196.
- Bazzaz, F.A. and Garbutt, K. (1988) The response of annuals in competitive neighbourhoods : effects of elevated CO₂. *Ecology*, **69**: 937-946.
- Bazzaz, F.A. and Miao, S.L. (1993) Successional status, seed size and responses of tree seedlings to CO₂, light and nutrients. *Ecology*, **74**: 104-112.

- Billes, G., Rouhier, H. and Bottner, P. (1993) Modifications of the carbon and nitrogen allocations in the plant (*Triticum aestivum* L.) soil system in response to increased atmospheric CO₂ concentration. *Plant and Soil*, **157**: 215-225.
- Bindi, M., Fibbi, L., Frabotta, A., Chiesi, M., Selvaggi, GT and Magliulo, V. (1999) Free Air CO₂ Enrichment of potato (*Solanum tuberosum* L.) In: *Annual report for changing climate and potential impacts of potato yield and quality (CHIP), Control, ENV4-CT97-0489*. pp. 160-196.
- Bindi, M., Fibbi, L., Gozzini, B., Orlandini, S. and Miglietta, F. (1995) Mini free air carbon dioxide enrichment (FACE) experiment on grapevine. In: *Climate Change and Agriculture in Europe: Assessment of Impacts and Adaptations, Research Report No. 9, Contract ENV4-CT97-0489* (P.A. Harrison, R.E. Butterfield and T.E. Downing, Eds.), Commission of the European Union, Brussels, Belgium, pp. 125-137.
- Blair, G.J., Lefroy, R.D.B. and Lisle, L. (1995) Soil carbon fractions based on their degree of oxidation and the development of a carbon management index for agricultural systems. *Australian Journal of Agricultural Research*, **46**: 1459-1466.
- Boerner, R.E.J. and Rebbeck, J. (1995) Decomposition and nitrogen release from leaves of three hardwood species grown under elevated O₃ and/or CO₂. *Plant and Soil*, **170**: 149-157.
- Bowen, W.T., Jones, J.W., Carsky, R.J. and Quintana, J.O. (1993) Evaluation of the nitrogen submodel of CERES-Maize following legume green manure incorporation. *Agronomy Journal*, **85**: 153-159.
- Bremner, J. and Keeney, D. (1966) Determination and isotope-ratio analysis of different forms of nitrogen in soils. III exchangeable ammonium, nitrate and nitrite by extraction-distillation methods. *Soil Science Society of America Proceedings*, **30**: 577-582.
- Brink, R.H., Dubach, P. and Lynch, D.L. (1960) Measurement of carbohydrate in soil hydrolysates with anthrone. *Soil Science*, **89**: 157-165.
- Brooks, T.J., Wall, G.W., Pinter, P.J., Kimball, B.A., LaMorte, R.L., Leavitt, S.W., Matthias, A.D., Adamsen, F.J., Hunsaker, D.J. and Webber, A.N. (2001) Acclimation response of spring wheat in a free air CO₂ enrichment (FACE) atmosphere with variable soil nitrogen regimes: Canopy architecture and gas exchange. *Photosynthesis Research*, **66**: 97-108.
- Burfod, J.R. and Bremner, I.M. (1975) Relationship between the denitrification capacities of the soil and total, water soluble and readily decomposable soil organic matter. *Soil Biology and Biochemistry*, **7**: 389-394.

- Canadell, J.G., Pitelka, L.F. and Ingram, J.S.I. (1996) The effects of elevated CO₂ on plant soil carbon below ground: A summary and synthesis. *Plant and Soil*, **187**: 391-400.
- Cardon, Z.G. (1996) Influence of rhizodeposition under elevated CO₂ on plant nutrition and soil organic matter. *Plant and Soil*, **187**: 277-288.
- Cave, T., Tolley, L.C. and Strain, B.R. (1981) Effects of carbon dioxide enrichment on chlorophyll content, starch content and starch grain structure in *Trifolium subterraneum* leaves. *Physiologia Plantarum*, **51**: 171-171.
- Centritto, M., Lee, H. and Jarvis, P.G. (1999) Increased growth in elevated CO₂ : an early short term response? *Global Change Biology*, **5**: 623-633.
- Chang, C.W. (1975) Carbon dioxide and senescence in cotton plants. *Plant Physiology*, **55**: 515-519.
- Chapin, F.S., III, Schulze, E.D. and Mooney, H.A. (1990) The ecology and economics of storage in Plants. *Annual Review of Ecological systems*, **21**: 423-447.
- Chaudhuri, U.N., Kirkham, M.B. and Kanemasu, E.T. (1990) Root growth of winter wheat under elevated carbon dioxide and drought. *Crop Science*, **30**: 853-857.
- Ciais, P., Tans, P.P., Trolier, M., White, J.W.C. and Francey, R.J. (1995) A large northern hemisphere terrestrial CO₂ sink indicated by the ¹³C/¹²C ratio of atmospheric CO₂, *Science*, 269:1098¹102.
- Coleman, J.S., McConnaughay, K.D.M., Bazzaz, F.A. (1993) Elevated CO₂ and plant nitrogen use: Is reduced tissue nitrogen concentration size dependent? *Oecologia*, **93**: 195-200.
- Collettee, E. (1995) Will plants profit from high CO₂? *Science*, **268**: 654-655.
- Conroy, J.P. (1992) Influence of elevated atmospheric CO₂ concentration on plant nutrition. *Australian Journal of Botany*, **40**: 445-456.
- Cortez, J., Demard, J.M., Bottner, P. and Monrozier, J.L. (1996) Decomposition of Mediterranean leaf litter: a microcosm experiment investigating relationships between decomposition rates and litter quality. *Soil Biology and Biochemistry*, **4-5**: 443-452.
- Cotrufo, M.F. and Ineson, P. (1995) Effects of enhanced carbon dioxide and nutrient supply on the quality and subsequent decomposition of fine roots of *Betula pendula* Roth. and *Picea sitchensis* (Bong) Carr. *Plant and Soil*, **170**: 267-277.

- Cotrufo, M.F. and Ineson, P. (1996) Elevated CO₂ reduces field decomposition rates of *Betula pendula* (Roth.) leaf litter. *Oecologia*, **106**: 525-530.
- Cotrufo, M.F., and Ineson, P. (2000) Does elevated atmospheric CO₂ concentrations affect wood decomposition? *Plant and Soil*, **224**: 51-57.
- Cotrufo, M.F., Ineson, P. and Rowland, A.P. (1994) Decomposition of tree leaf litters grown under elevated CO₂: Effect of litter quality. *Plant and Soil*, **163**: 121-130.
- Cotrufo, M.F., Ineson, P. and Scott, A. (1998) Elevated CO₂ reduces the nitrogen concentration of plant tissues. *Global Change Biology*, **4**: 43-54.
- Courteaux, M.M., Mousseau, M., Celerier, M.L. and Bottner P. (1991) Increased atmospheric CO₂ and litter quality: decomposition of sweet chestnut leaf litter with animal food webs of different complexities. *Oikos*, **61**: 54-64.
- Cure, J.D. (1985) Carbon dioxide doubling responses: a crop survey. In: *Direct Effects of Increasing Carbon Dioxide on Vegetation*, DOE/ER-0238 (B.R. Strain and J.D. Cure, Eds.), United States Department of Energy, Washington, DC. pp. 96-116.
- Cure, J.D. and Acock, B. (1986) Crop responses to carbon dioxide doubling: A literature survey. *Agricultural and Forest Meteorology*, **38**: 127-145.
- Curtis, P.S., Drake, B.G. and Whigham D.F. (1989) Nitrogen and carbon dynamics in C₃ and C₄ estuarine marsh plants grown under elevated CO₂ *in situ*. *Oecologia*, **78**: 297-301.
- Daepp, M., Nosberger, J. and Luscher, A. (2001) Nitrogen fertilization and developmental stage alter the response of *Lolium perenne* to elevated CO₂. *New Phytologist*, **150**: 347-358.
- Daepp, M., Suter, D., Almeida, J.P.F., Isopp, H., Hartwig, U., Frehner, M., Blum, H., Nosberger, J. and Luscher, A. (2000) Yield response of *Lolium perenne* swards to free air CO₂ enrichment increased over six years in a high N input system on fertile soil. *Global Change Biology*, **6**: 805-816.
- Daie, J. (1985) Carbohydrate partitioning and metabolism in crops. *Horticultural Reviews*, **7**: 69-108.
- De Leo, G.A., Rizzi, L, Cairri, A. and Cratto, M. (2001) Carbon emissions, The economic benefits of the Kyoto protocol. *Nature*, **413**: 428-479.
- Diaz, S., Grime, J.P., Harrish, J. and McPherson, E. (1993) Evidences of a feedback mechanism limiting plant response to elevated carbon dioxide. *Nature*, **364**: 616-617.

- Drake, B.G. (1992) A field study of the effects of elevated CO₂ enrichment on ecosystem processes in a chesapeake Bay Wetland. *Australian Journal of Botany*, **40**: 579-595.
- Drake, B.G., Leadley, P.W., Arp, W.J., Nassiry, D. and Curtis, P.S. (1989) An open top chamber for field studies of elevated atmospheric O₂ concentration on salt marsh vegetation. *Functional Ecology*, **3**: 363-371.
- Du Loux, H.C., Andre, M., Daguenet, A. and Massimino, J. (1987) Wheat responses to CO₂ exchange at two plant densities. *Journal of Experimental Botany*, **38**: 1421-1431.
- Dwivedi, N., Mohan, R. and Upreti, D.C. (1997) Interactive effect of rising atmospheric carbon dioxide and drought on the nutrient constituents of *Brassica juncea* seeds. *Science and Culture*, **63** (11-12): 291-292.
- Farrar, J.F. and Williams, M.L. (1991) The effects of increased atmospheric carbon dioxide and temperature on carbon partitioning, source sink relations and respiration. *Plant, Cell and Environment*, **14**: 818-830.
- Ford, M.A. and Thorne, G.N. (1967) Effect of CO₂ concentration on growth of sugarbeet, barley, kale and maize. *Annals of Botany*, **31**: 629-643.
- Gifford, R.M. (1982) Global photosynthesis in relation to our food and energy needs. In: *Photosynthesis II: Development, Carbon Metabolism and Plant Productivity*. (Govindjee, R. ed.), Academic Press, New York, pp. 459-495.
- Gifford, R.M. (1994) Whole plant respiration and photosynthesis of wheat under increased CO₂ concentration and temperature : long-term vs. short-term distinctions for modeling. *Global Change Biology*, **1**: 385-396.
- Gifford, R.M., Barrett, D.J., Lutze, J.L. (2000) The effect of elevated CO₂ on C:N and C:P mass ratio of plant tissues. *Plant and Soil*, **224**: 1-14.
- Gifford, R.M., Lutze, J.L. and Barret, D. (1996) Global atmospheric change effects on terrestrial carbon sequestration: Exploration with a global C and N cycle model (CQUESTN). *Plant and Soil*, **187**.
- Godwin, D.C. and Jones, C.A. (1991) Nitrogen dynamics in soil plant systems. In: *Modelling plant and soil systems. Agronomy Monograph 31*, (Ritchie, J.T. and Hanks, R.J. Eds.), Madison, WI, pp. 287-321.
- Gomez, K.A. and Gomez, A.A. (1984) *Statistical procedures for agricultural research*. John Wiley and sons, New York.
- Gorissen, A. (1996) Elevated CO₂ evokes quantitative and qualitative change in carbon dynamics in a plant/soil system: mechanisms and implications. *Plant and soil*, **187**: 289-298.

- Gorissen, A., Cotrufo, M.F. (2000) Decomposition of leaf and root tissue of three perennial grass species grown at two levels of atmospheric CO₂ and N supply. *Plant and Soil*, **224**: 75-84.
- Gorissen, A., Van Ginkel, J.H., Keurenjes, J.J.B. and Van Veen, J.A. (1995) Grass root decomposition is retarded when grass has been grown under elevated CO₂. *Soil Biology and Biochemistry*, **27**: 117-120.
- Gough, C.M. and Seiler, J.R. (2004) Belowground carbon dynamics in loblolly pine (*Pinus taeda*) immediately following diammonium phosphate fertilization. *Tree Physiology*, **24**(7): 845-851.
- Gregory, P.J., Palta, J.A. and Batts, G.R. (1997) Root systems and root:mass ratio carbon allocation under current and projected atmospheric conditions in arable crops. *Plant and Soil*, **187**: 221-228.
- Griffiths, B.S., Ritz, K., Ebbelwhite, N., Paterson, E. and Killham, K. (1998) Ryegrass rhizosphere microbial community structure under elevated carbon dioxide concentrations, with observations on wheat rhizosphere. *Soil Biology and Biochemistry*, **30**(3): 315-321.
- Hagedorn, F., Blaser, P. and Siegwolf, R. (2002) Elevated atmospheric CO₂ and increased N deposition effects on dissolved organic carbon clues from delta ¹³C signature. *Soil Biology and Biochemistry*, **34**(3): 355-366.
- Hagedorn, F., Spinnler, D., Bundt, M., Blaser, P. and Siegwolf, R. (2003) The input and fate of new C in two forest soils under elevated CO₂. *Global Change Biology*, **9**(6): 862-872.
- Hanway, J.J. and Heidel, H. (1952) Soil analysis methods as used in Iowa state college, soil testing laboratory. *Iowa Agriculture*, **54**: 1-31.
- Hardy, R.W.F. and Havelka, U.D. (1975) Photosynthate as a major factor limiting nitrogen fixation by field-grown legumes with emphasis on soybeans. In: *Symbiotic Nitrogen Fixation in Plants*. (Nutman, P.S. Ed.), International Biology Program Series. Vol. 7, Cambridge University Press, London, pp. 421-439.
- Harrison, K. G. (1996), Using bulk soil radiocarbon measurements to estimate soil organic matter turnover times: Implications for atmospheric CO₂ levels, *Radiocarbon*, **38**: 181-190.
- Harrison, K.G., Post, W.M. and Richter, D.D. (1995) Soil carbon turnover in a recovering temperate forest. *Global Biogeochemical Cycles* **9**: 449-454.
- Heagal, A.S., Body, D.E. and Heck, W.W. (1973) An open top chamber to assess the impact of air pollution on plant. *Journal of Environmental Quality*, **2**: 365-3968.

- Hebeisen, T., Luscher, A., Zanetti, S., Fischer, B.U., Hartwig, U.A., Frehner, M., Hendrey, G.R., Blum, H. and Nosberger, J. (1997) Growth response of *Trifolium repens* L. and *Lolium perenne* L. as monocultures and bi-species mixture to free air CO₂ enrichment and management. *Global Change Biology*, **3**: 149-160.
- Helal, H.M. and Sauerbeck, D. (1986) Effect of plant roots on carbon metabolism of microbial biomass. *Z. Pflanzenernaehr*, **149**: 181-188.
- Hendrey, G.R. (1993) Free air carbon dioxide enrichment for plant research in the field. Boca Raton, FL, USA.
- Hirshel, G., Korner, CH. and Arnone, J.A. (1997) Will rising atmospheric CO₂ affect leaf litter quality and *in situ* decomposition rates in native plant communities? *Oecologia*, **110**: 387-392.
- Hocking, P.J. and Meyer, C.P. (1991) Effects of CO₂ enrichment and nitrogen stress on growth, and partitioning of dry matter and nitrogen in wheat and maize. *Australian Journal of Plant Physiology*, **18**: 339-356.
- Honeycutt, C.W., Potaro, L.J., Avila, K.L. and Halteman, W.A. (1993) Residue quality, loading rate and soil temperature relations with hairy vetch (*Vicia villosa* Roth) residue carbon, nitrogen and phosphorus mineralization. *Biological Agriculture and Horticulture*, **9**: 181-199.
- Horwath, W.R. and Paul, E.A. (1994) Microbial Biomass. In: *Methods of soil Analysis, Part 2. Microbiological and Biochemical properties- SSSA Book series No. 5*, Soil Science Society of America, Madison, WI, USA, pp. 753-773.
- Houghton, J.I., Meira-Filho, L.G., Callandes, B.A., Harris, N., Kathenburg, A., Maskell, K. (1996) IPCC Climate Change Assessment 1995. In: *The Science of Climate Change*, Cambridge University Press, Cambridge.
- Houghton, J.T., Jenkins, G.J. and Ephrams, J.J. (1990) Climate change: The IPCC Scientific Assessment, Cambridge University Press, Cambridge.
- Houghton, J.T., Meira, Filho, L.G., Bruce, J., Lee, H., Callander, B.A., Hactes, E., Harris, N. and Maskell, K. (1995) Climate change 1994, IPCC combridge University press. New York, USA. pp. 339.
- Howard, P.J.A. and Howard, D.M (1974) Microbial decomposition of tree and shrub leaf litter. *Oikos*, **25**: 311-352.
- Hungate, B.A., Chapin, F.S., Zhong, H., Holland, E.A. and Field, C.B. (1997) Stimulation of grassland nitrogen cycling under carbon dioxide enrichment. *Oecologia*, **109**: 149-153.
- Hungate, B.A., Jackson, R.B., Field, C.B. and Chapin, F.S. (1996) Detecting charges in soil carbon in CO₂ enrichment experiments. *Plant and Soil*, **187**: 135-145.

- Hurrell, J.W. (1998) Relationship among recent atmospheric circulation changes, global warming and satellite temperature. *Science Progress*, **81**: 205-224.
- Idso, S.B. and Kimball, B.A. (1991) Downward regulation of photosynthesis and growth at high CO₂ levels: No evidence for either phenomenon in three year's study of sour orange trees. *Plant Physiology*, **96**: 990-992.
- Idso, S.B., Kimball, B.A. and Mauney, J.R. (1987) Atmospheric carbon dioxide enrichment effects on cotton midday foliage temperature : implications for plant water use and crop yield. *Agronomy Journal*, **79**: 667-672.
- Imai, K. and Murata, Y. (1976) Effect of carbon dioxide concentration on growth and dry matter production in crop plants. *Proceedings of Crop Science Society of Japan*, **45**: 598-606.
- Imai, K., Coleman, D.F. and Yanagisawa, T. (1985) Increase in atmospheric partial pressure of carbon dioxide and growth and yield of rice (*Oryza sativa* L.) *Japanese Journal of Crop Science*, **54**: 413-418.
- Insam, H., Parkinson, D. and Domsch, K.H. (1989) Influence of macroclimate on soil microbial biomass. *Soil Biology and Biochemistry*, **21**: 211-221.
- Inubushi, K., WeiGuo, C. and Chander, K. (1999) Carbon dynamics in submerged soil microcosms as influenced by elevated CO₂ and temperature. *Soil Science and Plant Nutrition*, **45**(4): 863-872.
- IPCC (2001) Science of climate change. Third Assessment Report (TAR) of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge.
- Islam, K.R., Mulchi, C.L., Ali, A.A. (1999) Tropospheric CO₂ or ozone enrichments and moisture effects on soil organic Matter Quality. *Journal of Environmental Quality*, **28**: 1629-1636.
- Johnson, D., Geisinger, D., Walker, R., Newman, J., Vose, J., Elliot, K. and Ball, T. (1994) Soil pCO₂, soil respiration, and root activity in CO₂-fumigated and nitrogen-fertilized ponderosa pine. *Plant and Soil*, **165**: 129-138.
- Jones, P., Jones, J.W. and Allen, L.H. Jr. (1985) Carbon dioxide effects on photosynthesis and transpiration during vegetative growth in soybeans. *Crop Science Society Florida Proceedings*, **44**: 129-134.
- Kant, P.C.B. (2004) Active pools of carbon in rhizospheres of wheat grown with elevated carbon dioxide concentration. M.Sc thesis, Indian Agricultural Research Institute, New Delhi.
- Keeling, C.D., Whorf, T.P., Wehlen, M., Van der Pliht, J. (1995) Inter annual extremes in the rate of rise in atmospheric carbon dioxide since 1980. *Nature*, **375**: 666-670.

- Keeling, R.F., S. C. Piper, and M. Heimann (1996) Global and hemispheric CO₂ sinks deduced from changes in atmospheric O₂ concentration, *Nature*, **381**: 218-221.
- Kemp, P.R., Waldecker, D.G., Owensby, C.E. and Reynolds, J.F. (1994) Effects of elevated CO₂ and nitrogen fertilization pretreatments on decomposition of tall grass prairie leaf litter. *Plant and Soil*, **165**: 115-127.
- Kim, H.Y., Lieffering, M., Miura, S., Kobayashi, K. and Okada, M. (2001) Growth and nitrogen uptake of CO₂ enriched rice under field conditions. *New Phytologist*, **150**: 223-230.
- Kimball, B.A. (1983) Carbon dioxide and agricultural yield- an assemblage and analysis of 430 prior observations. *Agronomy Journal*, **75**: 779-788.
- Kimball, B.A. (1986) Influence of elevated CO₂ on crop yield. In: *Carbon Dioxide Enrichment of Greenhouse Crops. Volume 2: Physiology, yield, and Economics*. (Enoch, H.Z. and Kimball, B.A. Eds.), CRC Press, Boca Raton, FL, pp. 105-115.
- Kimball, B.A. (1995) Adaptation of vegetation and management to higher carbon dioxide world. In: *Direct effect of increasing carbon dioxide on vegetation*. (Strain, B.R., Cure, J.D. Eds.), US department of Energy, Washington D.C, pp. 185-204.
- Kimball, B.A. and Idso, S.A.B. (1983) Increasing atmospheric CO₂: Effects on crop yield, water use, and climate. *Agricultural Water Management*, **7**: 55-72.
- Kimball, B.A., Kobayashi, K. and Bindi, M. (2002) Response of agricultural crops to free air CO₂ enrichment. *Advances in Agronomy*, **77**: 293-368.
- Kimball, B.A., Morris, C.F., Pinter, P.J. Jr., Wall, G.W., Hunsaker, D.J., Adamsen, F.J., LaMorte, R.L., Leavitt, S.W., Thompson, T.L., Mothias, A.D. and Brooks, T.J. (2001) Wheat grain quality as affected by elevated CO₂, drought and soil nitrogen. *New Phytologist*, **150**: 295-303.
- Kimball, B.A., Pinter, P.J., Jr., Wall, G.W., Garcia, R.L. LaMorte, R.L., Jak, P.M.C., Framau, K.F.A. and Vughts, H.F. (1997) Comparisons of responses of vegetation to elevated carbon dioxide in free-air and open-top chamber facilities. In: *Advances in Carbon Dioxide Research* (Allen, L.H., Kirkham, M.B., Olszyk, D.M. and Whitman, C.E., Eds.), American Society of Agronomy, Crop Science Society of America and Soil Science Society of America, Madison, WI, pp. 113-130.

- King, J.S., Pregitzer, K.S., Zak, D.R., Kubiske, M.E., and Holmes, W.E. (2001) Correlation of foliage and litter chemistry of sugar maple, *Acer saccharum*, as affected by elevated CO₂ and varying N availability, and effects on decomposition. *Oikos*, **94**(3): 403-416.
- Klein, D.A., Loh, T.C. and Goulding, R.L. (1971) A rapid procedure to evaluate dehydrogenase activity of soils low in organic matter. *Soil Biology and Biochemistry*, **3**: 385-387.
- Kobayahsi, K., Kieffering, M. and Kim, H.Y. (2001) Growth and yield of paddy rice under free-air CO₂ enrichment. In: *Structure and Function in Agro ecosystem Design and Management* (Shiyomi, M. and Koizumi, H., Eds.), CRC Press, Boca Raton, F.L, pp. 371-395.
- Korner, C. and Arnone, J.A. (1992) Responses to elevated carbon dioxide in artificial tropical ecosystems. *Science*, **257**: 1672-1675.
- Kriedemann, P.E. and Wong, S.C. (1984) Growth response and photosynthetic acclimation to CO₂: comparative behaviour in two C₃ crop species. *Acta Horticulture*, **162**: 113-120.
- Kumari, S., Uprety, D.C., Dwivedi, N and Mohan. R. (1998) Effect of elevated CO₂ on the growth and yield of rice variety 'Pusa 834'. *Journal of Agronomy and Crop Science*, **180**: 7-13.
- Lambers, H (1993) Rising CO₂, secondary plant metabolism, plant herbivore interactions and litter decomposition. *Vegetatio*, **104/105**: 263-271.
- Lamborg, M.R., Hardy, R.W.F. and Paul, E.A. (1983) Microbial effects. In: *CO₂ and plants*. (Lemon, E.R., Ed.), AAAS selected symposium No. 84. Westview Press, Bolder, Colorado, pp. 131-176.
- Lawlor, D.W., Mitchell, R.A.C. (1991) The effect of increasing CO₂ on crop photosynthesis and productivity: a review of field studies. *Plant Cell and Environment*, **14**: 807-918.
- Lekkerkerk, L.J.A., Van de Geijn, S.C. and Van Veen, J.A. (1990) Effects of elevated atmospheric CO₂ levels on the carbon economy of a soil planted with wheat. In: *Soils and the Greenhouse Effect*. (Bouwman, A.F., Ed.), John Wiley, New York, pp. 423-429.
- Lewis, J.D., Thomas, R.B. and Strain B.R. (1992) Interactive effects of nutrient supply and elevated CO₂ on response of seedlings from two populations of *Pinus taeda* to mycorrhizal infection. *Bulletin of Ecological Society America*, **73**(Suppl), 249.
- Loya, W.M., Pregitza, K.S., Karbery, N.J., King, J.S. and Giardian, C.P. (2003) Reduction of soil carbon for nation by troposphere ozone under increased carbon dioxide levels. *Nature*, **425**: 705-707.

- Luo, Y., Wan, S., Hui, D. and Wallace, L.L. (2001) Acclimatization of soil respiration to warming in a tall grass prairie *Nature*, **413** (11): 622-625.
- Lutze, J.L. and Gifford, R.M. (1995) Carbon storage and productivity of a carbon dioxide enriched nitrogen limited grass sward after one year's growth. *Journal of Biogeography*, **22**: 1231-1237.
- Luxmoore, R.J. (1981) CO₂ and phytomass. *Bio Science*, **31**: 626.
- Luxmoore, R.J., O'Neill, E.G., Ells, J.M. and Rogers, H.H. (1986) Nutrient uptake and growth response of Virginia pine to elevated atmospheric carbon dioxide. *Journal of Environmental Quality*, **15**: 244-251.
- Marilley, L., Hartwing, U.A. and Arognio, M. (1999) Influence of an elevated atmospheric CO₂ content on soil and rhizosphere bacterial communities beneath *Lolium perenne* and *Trifolium repens* under field conditions. *Microbial Ecology*, **39**: 39-49.
- Masle, J., Farquhar, G.D. and Gifford, R.M. (1990) Growth and carbon economy of wheat seedlings as affected by soil resistance to penetration and ambient partial pressure of CO₂. *Australian Journal of Plant Physiology*, **17**: 465-487.
- Mauney, J.R., Kimball, B.A., Pinter, P.J., Jr., LaMorte, R.L., Lewin, K.F., Nagy, J. and Hendrey, G.R. (1994) Growth and yield of cotton in response to a free-air carbon dioxide enrichment (FACE) environment. *Agricultural and Forest Meteorology*, **70**: 49-68.
- Mauney, J.R., Lewin, K.F., Hendrey, G.R. and Kimball, B.A. (1992) Growth and yield of cotton exposed to free air CO₂ enrichment (FACE) *Critical Reviews in Plant Science*, **11**: 213-222.
- McGuire, A.D., Melillo, J.M. and Joyce, L.A. (1995) The role of nitrogen in the response of forest net primary production to elevated atmospheric carbon dioxide. *Annual Review of Ecological Systems*, **26**: 473-503.
- Melillo, J.M. (1983) Will increases in atmospheric CO₂ concentrations affect litter decay rates? In: *The ecosystems center annual report*. Marine Biological Laboratory, Woods Hole, Massachusetts, USA, pp 10-11.
- Melillo, J.M., Aber, J.D. and Muratore, J.F. (1982) Nitrogen and lignin control of hardwood leaf litter decomposition dynamics. *Ecology*, **6**: 621-626.
- Miglietta, F., Magliulo, V., Bindi, M., Cerio, L., Vaccari, F.P., Loduca, V. and Peressotti, A. (1998) Free Air CO₂ Enrichment of potato (*Solanum tuberosum* L.) development, growth and yield. *Global Change Biology*, **4**: 163-172.

- Mitchell, R.A.C., Mitchell, V., Driscoll, S.P., Franklin, J. and Lawlor, D.W. (1995) Effects of increasing CO₂ concentration and temperature on growth and yield of winter wheat at two levels of nitrogen application. *Plant Cell and Environment*, **16**: 521-529.
- Montealegre, C.M., Van Kessel, C., Blumental, J.M., Hur, H.G., Hartwing, U.A. and Sandwsky, M.J. (2000) Elevated atmospheric CO₂ alters microbial population structure in a pasture ecosystem. *Global Change Biology*, **6**: 475-482.
- Moore, B.D., Cheng, S.H., Sims, D. and Seemann, J.R. (1999) The biochemical and molecular basis for photosynthetic acclimation to elevated atmospheric CO₂. *Plant, Cell and Environment*, **22**: 567-582.
- Morison, J.I.L. (1988) Sensitivity of stomata and water use efficiency to high CO₂. *Plant, Cell and Environment*, **8**: 467-474.
- Morison, J.I.L. (1996) Global environmental change impacts on crop growth and production in Europe. Implications of global environmental change for crops in Europe. *Aspects of Applied Biology*, **45**: 15-29.
- Mott, K.A. (1990) Sensing of atmospheric CO₂ by plants. *Plant, Cell and Environment*, **13**: 731-737.
- Moya, T.B., Ziska, L.W., Namuco, O.S. and Olszyk, D. (1998) Growth dynamics and genotypic variations in tropical, field grown paddy rice (*Oryza sativa* L.) in response to increasing carbon dioxide and temperature. *Global Change Biology*, **4**: 645-656.
- Nakayama, F.S. and Kimball, B.A. (1988) Soil carbon dioxide distribution and flux within open top chamber. *Agronomy Journal*, **80**: 394-398.
- Neales, T.F. and Nicholls, A.O. (1978) Growth responses of young wheat plants to a range of ambient CO₂ levels. *Australian Journal of Plant Physiology*, **5**: 45-59.
- Norby, R.J., Gunderson, C.A., Wullschleger, S.D., O'Neill, E.G. and McCracken, M.K. (1992) Productivity and compensatory responses of yellow poplar trees in elevated CO₂. *Nature*, **354**: 322-324.
- Norby, R.J., O'Neill, E.G. and Luxmoore, R.J. (1986) Effects of CO₂ enrichment on the growth and mineral nutrition of *Quercus alba* seedling in nutrition poor soil. *Plant Physiology*, **82**: 83-89.
- Norby, R.J., O'Neill, E.G., Hood, W.G. and Luxmoore, R.J. (1987) Carbon allocation, root exudation and mycorrhizal colonization of *Pinus echinata* seedlings grown under CO₂ enrichment. *Tree Physiology*, **3**: 203-210.

- Norby, R.J., Wullschlegel, S.D., Gunderson, C.A., Hohnson, D.W. and Ceulemans, R. (1999) Tree response to rising CO₂ in field experiments: implication for the future forest. *Plant Cell and Environment*, **22**: 683-714.
- O'Neill, E.G. (1994) Responses of soil biota to elevated atmospheric carbon dioxide. *Plant and Soil*, **165**: 55-65.
- O'Neill, E.G. and Norby, R.J. (1996) Litter quality and decomposition rates of foliar litter produced under CO₂ enrichment. In: *Carbon dioxide and terrestrial eco-systems*. (Koch G.W. and Mooney, H.A. Eds.), Academic press, San Diego, pp. 87-103.
- O'Neill, E.G., and Norby, R.J. (1991) First year decomposition dynamics of yellow poplar leaves produced under CO₂ enrichment. *Bulletin of Ecological Society of America*, **72**: 208.
- O'Neill, E.G., Luxmoore, R.J. and Norby, R.J. (1987) Elevated atmospheric CO₂ effects on seedling growth, nutrient uptake and rhizosphere bacterial populations of *Liriodendron tulipifera* L. *Plant and Soil*, **104**: 3-11.
- Oberbauer S.F., Sionit, N., Hastings, S.J. and Oechel, W.C. (1986) Effects of CO₂ enrichment and nutrition on growth, photosynthesis and nutrient concentration of Alaskan tundra grasses. *Canadian Journal of Botany*, **64**: 2993-2998.
- Olsen, S.R., Cole, C.V., Watanable, F. and Dean, L.A. (1954) Estimation of available phosphorus in soils by extraction with sodium bicarbonate. Circular, U.S. Department of Agriculture, pp. 939.
- Ottman, M.J., Kimball, B.A., Printer, P.J., Jr., Wall, G.W., Wanderlip, R.L., Leavitt, S.W., Lamorte, R.L., Matthisa, A.D. and Brooks, T.J. (2001) Elevated CO₂: Effects on sorghum growth and yield at high and low soil water content. *New Phytologist*, **150**: 261-273.
- Owensby, C.E., Coyne, P.I., Aven, L.M. (1993) Nitrogen and phosphorus dynamics of a tallgrass prairie ecosystem exposed to elevated carbon dioxide. *Plant, Cell and Environment*, **16**: 843-850.
- Padre, A.T., Alumagam, M. and Ladha, J.K. (2001) Estimating soil labile C by KMnO₄ oxidation as an early indicator of changes in the soil organic matter pool. *Asian Agriculture Congress report*. Manila (Philippines). pp. 24-27.
- Padre, T.A. and Ladha, J.K. (2004) Assessing the reliability of permanganate oxidisable carbon as an index of soil labile carbon. *Social Science Society of America Journal*, **68**(3): 969-978.

- Parton, W.J., Schimel, D.S., Cole, C.V., and Ojima, D.S. (1986) Analysis of factors controlling soil organic matter levels in Great Plains grasslands. *Soil Science Society of America Journal*, **51**: 1173-1179.
- Paterson, E., Rattray, E.A.S and Killham, K. (1996) Effect of elevated atmospheric CO₂ concentration on C-partitioning and rhizosphere C-flow for three plant species. *Soil Biology and Biochemistry*, **28**(2): 195-201.
- Patterson, D.T. and Flint, F.P. (1980) Potential effects of global atmospheric CO₂ enrichment on the growth and competitiveness of C₃ and C₄ weeds and crop plants. *Weed Science*, **28**: 71-75.
- Paustrian, K., Elliott, E.T., Peterson, G.A. and Killian, K. (1996) Modeling climate, CO₂ and management impacts on soil carbon in semiarid agroecosystems. *Plant and Soil*, **187**.
- Petit, J.R., Jouzel, J.D., Barnola, S.M. and Basile, (1999) Climate and atmospheric history of past, 4,20,000 years from vostok ice core, Antarctica. *Nature*, **399**: 429-436.
- Pinter, P. Jr., Kimball, B., Garcia, R., Wall, G., Hunsaker, D. and LaMorte, R. (1996) Free-air CO₂ enrichment of cotton and wheat crops. In: Carbon dioxide and terrestrial ecosystems. (Koch, G. and Mooney, H., Eds.), Academic Press, San Diego, pp. 215-250.
- Pinter, P.J., Kimball, B.A., Wall, G.W., LaMorte, R.L., Leavitt, S.W., Hunsaker, D.J., Adamsen, F.J., Wechsung, T.J., Thompson, T.L., Kartschall, T. F., Wechsung, G., Garcia, R.L., Matthias, A.D and Brooks, T.J. (1997a) Free air carbondioxide enrichment (FACE) blower effect on wheat canopy microclimate and plant development. *Agricultural and Forest Meteorology* **103**: 319-333.
- Pinter, P.J., Kimball, B.A., Wallll, G.W., LaMortee, R.L., Adamseen, F.J. and Hunsaker, D.J. (1997b) Effects of elevated CO₂ and soil nitrogen fertilizer on final grain yields of spring wheat. In: *Annual Research Report, U.S. Water Conservation Laboratory, USDA, Agricultural Research Service*, Phoenix, AZ, pp. 71-74.
- Polle, A., Mckee, I. and Blaschke, L. (2001) Altered physiological and growth responses to elevated CO₂ in offspring from holm oak (*Qauercus ilex* L.) mother trees with life time exposure to naturally elevated CO₂. *Plant, Cell and Environment*, **24**: 1075-1083.
- Poorter, H. (1993) Interspecific variation in the growth response of plants to an elevated ambient CO₂ concentration. In: *CO₂ and Biosphere* (Rozema, J., Lambers, H., Van de Geijn, S. and Cambridge, M.L., Eds.), Kluwer Academic Publishers, Dordrecht, Netherlands, pp. 77-79.

- Porter, M.A. and Grodzinski, B. (1984) Acclimation of high CO₂ in bean. *Plant Physiology*, **74**: 413-416.
- Powlson, D. (2005) Will soil amplify climate change? *Nature*, **433**(20): 204-205.
- Prescott, C.E., Corbin J.P. and Parkinson, D. (1989) Biomass productivity and nutrient use efficiency of above ground vegetation found in Rocky Mountain coniferous forests. *Canadian Journal of Forest Research*, **19**: 309-317
- Prior, S.A., Torbert, H.A., Runion, G.B., Mullins, G.L., Rogers, H.H. and Mauney, J.R. (1998) Effects of carbon dioxide enrichment on cotton nutrient dynamics. *Journal of Plant Nutrition*, **21**: 1407-1426.
- Prior, S.A., Torbert, H.A., Runion, G.B., Rogers, H.H., Wood, C.W., Kimball, B.A., LaMorte, R.L., Pinter, P.J. and Wall, G.W. (1997) Free air carbon dioxide enrichment of wheat : soil carbon and nitrogen dynamics. *Journal of Environmental Quality*, **26**: 1161-1166.
- Quemada, M. and Cabrera, M.L. (1995) CERES-N model predictions of nitrogen mineralized form cover crop residues. *Soil Science Society of America Journal*, **59**: 1059-1065.
- Randlett, D.L., Zak, D.R., Pregitzer, K.S. and Curtis, P.S. (1996) Elevated atmospheric carbon dioxide and leaf litter chemistry: influences on microbial respiration and net nitrogen mineralization. *Soil Science Society of America Journal*, **60**(5): 1571-1577.
- Rastetter, E.B., Mckane, R.B., Shaver, G.R. and Melillo, J.M. (1992) Changes, in C storage by terrestrial ecosystems: How C-N interactions restrict responses to CO₂ and temperature. *Water, Air and Soil Pollution*, **64**: 327-344.
- Rayner and Boddy (1986) Fungal Decomposition of Wood. (John Wiley and Sons Eds.), Chichester.
- Rayner, P.J., Enting, I.G., Francey, R.J. and Langenfelds, R. (1999) Reconstructing the recent carbon cycle from atmospheric CO₂, ¹³C and O₂/N₂ observations, *Tellus Series A*, **51**: 213-232.
- Rillig, M.C., Wright, S.F., Kimball, B.A., Pinter, P.J., Wall, G.W., Adam, N.R., LaMorte, R.L., Ottman, M.J., Leavitt, S.W., Matthias, A.D., Thompson, T.L., Williams, D.G. and Brooks, T.J. (2001) Elevated carbon dioxide (Free Air Carbon dioxide Enrichment, FACE) and irrigation effects on water stable aggregates in a sorghum field: a possible role for arbuscular mycorrhizal fungi. *Global Change Biology*, **7**: 333-337.

- Rogers, G.S., Milham, P.J., Thibaud, M.C., Conroy, J.P. (1996) Interaction between rising CO₂ concentration and nitrogen supply in cotton. I. Growth and leaf nitrogen concentration. *Australian Journal of Plant Physiology*, **23**: 119-125.
- Rogers, H.H., Bingham, G.E., Cure, J.D., Smith, J.M. and Surano, K.A. (1983) Responses of selected plant species to elevated carbon dioxide in the field. *Journal of Environmental Quality*, **12**: 569-574.
- Rogers, H.H., Cure, J.D., Thomas, J.F. and Smith, J.M. (1986) Soybean growth and yield response to elevated carbon dioxide. *Agriculture, Ecosystem and Environment*, **16**: 113-128.
- Rogers, H.H., Prior, S.A. and O'Neill, E.G. (1992) Cotton root and rhizosphere responses to free air CO₂ enrichment. *Critical Reviews in Plant Science*, **11**: 229-248.
- Rogers, H.H., Runion, G.B. and Krupa, S.V. (1994) Plant responses to atmospheric CO₂ enrichment with emphasis on roots and rhizosphere. *Environmental Pollution*, **83**: 155-189.
- Runion, G.B., Curl, E.A., Rogers, H.H., Backman, P.A., Rodriguez-Kabana, R. and Helms, B.E. (1994) Effects of Free Air CO₂ Enrichment on microbial populations in the rhizosphere and phyllosphere of cotton. *Agricultural and Forest Meteorology*, **70**: 117-130.
- Schappi, B and Korner, C.H. (1996) Growth responses of an alpine grassland to elevated CO₂. *Oecologia*, **105**: 43-52.
- Schappi, B and Korner, C.H. (1997) *In situ* effects of elevated CO₂ on the carbon and nitrogen status of alpine plants. *Functional Ecology*, **11**: 290-299.
- Schimel, D.S., Braswell, B.H., Holland, E.A., McKeown, R., Ojima, D.S., Painter, T.H., Parton, W.J. and Townsend, A.R. (1994), Climatic, edaphic, and biotic controls over storage and turnover of carbon in soils, *Global Biogeochemical Cycles*, **8**: 279-293.
- Schlesinger, W.H. (1984) Soil organic matter : a source of atmospheric CO₂. In: *The Role of Terrestrial Vegetation in the Global Carbon Cycle*. (Woodwell, G.M., Ed.), John Wiley, New York, pp. 111-127.
- Schlesinger, W.H. (1990) Evidence from chronosequence studies for a low carbon-storage potential of soils. *Nature*, **384**: 232-234.
- Schlesinger, W.H. and Lichter, J. (2001) Limited carbon storage in soil and litter of experimental forest plots under increased atmospheric CO₂. *Nature*, **411**(6836): 466-469.

- Schortemeyer, M., Hartwing, U.A., Hendrey, G.R. and Sadowsky, M.J. (1996) Microbial community changes in the rhizosphere of white clover and perennial ryegrass exposed to free air carbon dioxide enrichment (FACE) *Soil Biology and Biochemistry*, **28**: 1717-1724.
- Schulze, E.D. (1983) Root shoot interactions and plant life forms. *Netherland Journal Agricultural Sciences*, **4**: 291-303.
- Seligman, N.C. and Van Keulen, H. (1981) PAPRAN: A simulation model of annual pasture production limited by rainfall and nitrogen, In *Simulation of nitrogen behavior of soil plant systems*. (Frissel, M.J. and Van Veen, J.A., Eds.) PUDOC publishers, Wageningen, Netherlands, pp. 192-221.
- Sengupta, U.K. (1998) Effect of increasing CO₂ concentration on photosynthesis and photorespiration in wheat. *Current Science*, **57**: 145-146.
- Sharma, A. and Sengupta, U.K. (1990) Carbon dioxide enrichment effect on photosynthesis and related enzymes in *Vigna radiata*. *Indian Journal of Plant Physiology*, **33**: 340-346.
- Shrestha, R.K., Ladha, J.K. and Lefroy, R.D.B. (2002) Carbon management for sustainability of an intensively managed rice-based cropping system. *Biology and Fertility of Soils*, **36** (3): 215-223.
- Sinclair, T.R., Pinter, P.J., Kimball, B.A., Adamsen, F.J., LaMorte, R.L., Wall, G.W., Hunsaker, D.J., Adam, N.R., Broos, T.J., Garcia, R.L., Thompson, T.L., Leavitt, S.W. and Matthias, A.D. (2000) Leaf nitrogen concentration of wheat subjected to elevated CO₂ and either water or nitrogen deficits. *Agriculture, Ecosystem and Environment*, **79**: 53-60.
- Smith, J.L. and Paul, E.A. (1990) The significance of soil microbial biomass estimations. In: *Soil Biochemistry*. (Bollag, J. and G. Stotsky, G., Eds.), Mercel Dekker, New York, pp. 357-393.
- Snyder, J.D. and Trfymow, J.A. (1984) A rapid accurate wet oxidation diffusion procedure for determining organic and inorganic carbon in plant and soil samples. *Communications in Soil Science and Plant Analysis*, **15**(15): 587-597.
- Sowerby, A., Blum, H., Gray, T.R.G. and Ball, A.S. (2000) The decomposition of *Lolium perenne* in soil exposed to elevated CO₂: Comparisons of mass loss of litter with soil respiration and soil microbial biomass. *Soil Biology and Biochemistry*, **32**: 1359-1366.
- Stanford, G. and Schwaninger, F.M. (1973) Temperature coefficient of soil nitrogen mineralization. *Soil Science*, **115**: 321-323.

- Strain, B.R. and Bazzaz, F.A. (1983) Terrestrial plant communities. In: *CO₂ and Plants (AAAS selected symposium 84)*. (Lemon, E.R Ed.), Westview. Press, Boulder, pp. 177-222.
- Subbiah, B.V. and Asija, G.L. (1956) A rapid procedure for the determination of available nitrogen in soil. *Current Science*, **25**: 259-260.
- Susanna Marchi., Roberto Tognetti, , Francesco Primo Vaccari, Mario Lanini, Mitja Kaligarić, Francesco Miglietta and Antonio Raschi (2004) Physiological and morphological responses of grassland species to elevated atmospheric CO₂ concentrations in FACE-systems and natural CO₂ springs *Functional Plant Biology*, **31**: 181-194.
- Swift, M.J., Heal, O.W. and Anderson, J.M. (1979) Decomposition in terrestrial ecosystems. Blackwell Oxford.
- Tans, P.P. and Bakwin, P.S. (1995) Climate change and carbon dioxide forever. *Ambio Journal of Human Environment*, **24**: 376-378.
- Taylor, B.P., Parkinson, d. and Parsons, W.F.J. (1989) Nitrogen and lignin content as predictor of litter decay rates: a microcosm test. *Ecology*, **70**: 97-104.
- Technicon Monograph, (1971) Technicon Private Ltd. Tarrytown, New York.
- Thomas, R.B. and Strain, B.R. (1991) Root restriction as a factor in photosynthetic acclimation of cotton seedlings grown in elevated carbon dioxide. *Plant Physiology*, **96**: 627-634.
- Tolbert, N.E., Zeltich, I. (1983) Carbon metabolism. In: *CO₂ and plants: The Response of Plant to Rising Levels of Atmospheric Carbon Dioxide*. (Lemon, E.R Ed.), Westview Press, Boulder, pp. 21-64.
- Torbert, H.A., Prior, S.A. and Rogers, H.H. (1995) Elevated atmospheric carbon dioxide effects on cotton plant residue decomposition. *Soil Science Society of America Journal*, **59**: 1321-1328.
- Torbert, H.A., Prior, S.A., Rogers, H.H. and Runion, G.B. (1998) Crop residue decomposition as affected by growth under elevated atmospheric CO₂. *Soil Science*, **163**: 412-419.
- Torbert, H.A., Prior, S.A., Rogers, H.H. and Wood, C.W. (2000) Review of elevated atmospheric CO₂ effects on agro-ecosystems: residue decomposition processes and soil C storage. *Plant and Soil*, **224**: 59-73.
- Tscherko, D., Kandeler, E. and Jones, T.H. (2001) Effect of temperature on below-ground N-dynamics in a weedy model ecosystem at ambient and elevated atmospheric CO₂ levels. *Soil Biology and Biochemistry*, **33** (4/5): 491-501.

- Upreti, D.C. (1998) Carbon dioxide enrichment research and technology : open top chambers a new tool for global climate research. *Journal of Scientific Industrial Research*, **57**: 266-270.
- Upreti, D.C. and Mahalakshmi, V. (2000) Effect of elevated CO₂ and nitrogen nutrition on some physiological characters of *Brassica juncea*. *Journal of Agronomy and Crop Science*, **184**: 287-296.
- Upreti, D.C. and Mahalakshmi, V. (1996) Effect of elevated CO₂ and nitrogen nutrition on some physiological characters of *Brassica juncea*. *Journal of Agronomy and Crop Science*, **175**: 231-237.
- Upreti, D.C., Garg, S.C., Tiwari, M.K. and Mitra, A.P. (2000) Crop responses to elevated CO₂: Technology and Research (Indian studies) *Global Environment Research* (Japan), **3**(2): 155-167.
- Upreti, D.C., Dwivedi, N., Jain, V. and Mohan, R. (2003) Response of rice cultivars to elevated CO₂. *Biologia Plantarum*, **46**(1): 35-39.
- Upreti, D.C., Dwivedi, N., Saxena, D.C., Raj, A. and Paswan, G. (2004) Impact of enhanced CO₂ on plant growth. *Agriculture, Forestry and Natural Ecosystem*, pp. 19-22.
- USGS (2000) US Geological Survey World Petroleum Assessment. 2000: Description and results. Version 1.0 Reston, VA (S.O.) US Geological Survey digital data series. site: pubs.usgs.gov/dds/dds-060/espt.html.
- Van de Geijn, S.C. and Van Veen, J.A. (1993) Implications of increased carbon dioxide levels for carbon input and turnover in soils. *Vegetatio*, **104/105**: 283-292.
- Van Ginkel, J.H., Gorissen, A. and Van Veen, J.A. (1996) Long term decomposition of grass roots as affected by elevated CO₂ concentrations. *Journal of Environmental Quality*, **25**: 1122-1128.
- Van Veen, J.A., Liljeroth, E., Lekkerkerk, L.J.A. and Van de Geijn, S.C. (1991) Carbon fluxes in plant soil systems at elevated atmospheric CO₂ levels. *Ecological Applications*, **1**: 175-181.
- Van, Kessel, C., Nitschelm, J., Horwarth, W.R., Harris, D., Walley, F. Luscher, A. and Hartwing, U. (2000) Carbon-13 input and turn over in a pasture soil exposed to long-term elevated atmospheric CO₂. *Global Change Biology*, **6**: 123-135.
- Van, Veen, J.H., Gorissen, A. and Van Veen, J.A. (1996) Long term decomposition of grass roots as affected by elevated CO₂ concentrations. *Journal of Environmental Quality*, **25**: 1122-1128.

- VEMAP Members (1995) Vegetation/ecosystem modelling and analysis project: Comparing biogeography and biogeochemistry models in a continental scale study of terrestrial ecosystem responses to climate change and CO₂ doubling. *Global Biogeochemical Cycles*, **9**: 407-437.
- Vigil, M.F., Kissel, D.E. and Shith, S.J. (1991) Field crop recovery and modeling of nitrogen mineralized form labeled sorghum residues. *Soil Science Society of America Journal*, **55**: 1031-1037.
- Waggoner, M.G. (1989) Time of desiccation effects on plant composition and subsequent nitrogen release from several winter annual cover crops. *Agronomy Journal*, **87**: 236-241.
- Walkley, A. and Black, I.A. (1934) Estimation of soil organic carbon by dromice acid method. *Soil Science*, **37**: 29-38.
- Wall, G.W., Brooks, T.J., Adam, N.R., Cousins, A.B., Kimball, B.A., Pinter, P.J., LaMorte, R.L., Triggs, J., Ottman, M.J, Leavitt, S.W., Matthias, A.D., Williams, D.G. and Webber, A.N. (2001) Elevated atmospheric CO₂ improved sorghum plant water status by ameliorating the adverse effects of drought. *New Phytologist*, **152**: 231-248.
- WB (2001) Human Development Report. Oxford University Press.
- Wechsung, F., Garcia, R.L., Wall, G.W., Kartschall, T., Kimball, B.A., Michaelis, P., Pinter, P.J., Wewchsung, G., Grossman-Clarke, S., LaMorte, R.L., Adamsen, F.J., Leavitt, S.W., Thompson, T.L., Matthias, A.D. and Brooks, T.J. (2000) Photosynthesis and conductance of spring wheat ears: field response to free air CO₂ enrichment and limitations in water and nitrogen supply. *Plant, Cell and Environment*, **23**: 917-929.
- Wechsung, G., Wechsung, F., Wall, G.W., Adamsen, F.J., Kimball, B.A., Pinter, P.J., LaMorte, R.L., Garcia, R.L. and Kartschall, T. (1999) The effects of Free Air CO₂ Enrichment and soil water availability on spatial and seasonal patterns of wheat root growth. *Global Change Biology*, **5**: 519-529.
- Wong, S.C. and Osmond, C.B. (1991) Elevated atmospheric partial pressure of CO₂ and plant growth. III. Interactions between *Triticum aestivum* (C₃) and *Echinochloa frumentacea* (C₄) during growth in mixed culture under different CO₂, N, nutrition and irradiance treatments, with emphasis on below ground responses estimated using $\delta^{13}\text{C}$ value of root biomass. *Australian Journal of Plant Physiology*, **18**: 137-152.
- Wood, C.W., Torbert, H.A., Rogers, H.H., Runion, G.B. and Prior, S.A. (1994) Free Air CO₂ Enrichment effects on soil carbon and nitrogen. *Agricultural and Forest Meteorology*, **70**: 103-116.

- Zak, D.R., Pregitzer, K.S., Curtis, P.S., Teeri, J.A., Fogel, R. and Randlen, D.L. (1993) Elevated atmospheric CO₂ and feedback between carbon and nitrogen cycles. *Plant and Soil*, **151**: 105-117.
- Zak, D.R., Pregitzer, K.S., King, J.S. and Holmes, W.E. (2000) Elevated atmospheric CO₂, fine roots and the response of soil microorganisms: a review and hypothesis. *New Phytologist*, **147**: 201-222.
- Zanetti, S., Hartwig, U.A., Luscher, A., Hebeisen, T., Frehner, M., Fischer, B.U., Hendrey, G.R. Blum, H. and Nosberger, J. (1996) Stimulation of symbiotic N₂ fixation in *Trifolium repens* L. under elevated atmospheric pCO₂ in a grassland ecosystem. *Plant Physiology*, **112**: 575-583.
- Ziska, L.H., Namuco, O.S., Moya, T.B. and Quilang, J. (1997) Growth and yield responses of field-grown tropical rice to increasing carbon dioxide and air temperature. *Agronomy Journal*, **89**: 45-53.
- Ziska, L.H., Weerakoon, W., Namuco, O.S. and Pamplona, R. (1996) The influence of nitrogen on the elevated CO₂ response in field grown rice. *Australian Journal of Plant Physiology*, **23**: 45-52.

APPENDIX

Common acronyms used

BB	- Maximum nitrification rate
CARB	- Carbohydrate
CELL	- Cellulose
CERES	- Cereal simulation
CHC	- Carbohydrate carbon
CNRF	- C:N ratio factor
CRI	- Crown root initiation
DAS	- Days after sowing
DAT	- Days after transplanting
DMRT	- Duncan's multiple range test
DOC	- Dissolved organic carbon
FACE	- Free air carbon dioxide enrichment
FC	- Field capacity
FOM	- Fresh organic matter
FON	- Fresh organic nitrogen
GHG	- Greenhouse gas
HI	- Harvest index
HUM	- Humus
IPCC	- Intergovernmental panel on climate change
IRGA	- Infrared gas analyzer

LBC	- Labile carbon
LIGN	- Lignin
MBC	- Microbial biomass carbon
MF	- Moisture factor
MOP	- Muriate of potash
OTC	- Open top chamber
PID	- Proportional integral differential
PVC	- Poly vinyl chloride
RA	- Ambient CO ₂ - grown rice residues
RDECR	- Decay rate constant
RE	- Elevated CO ₂ - grown rice residues
SOM	- Soil organic matter
SSP	- Single superphosphate
ST	- Soil temperature
TF	- Temperature factor
TOC	- Total organic carbon
TSC	- Total soil carbon
WA	- Ambient CO ₂ - grown wheat residues
WE	- Elevated CO ₂ - grown wheat residues
WP	- Wilting point
WTREM	- Per cent weight remaining

T-7577

