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Biomass Production Chamber Air Analysis of Wheat Study (BWT931)

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ABSTRACT

NASA's Controlled Ecological Life Support System (CELSS) biomass production chamber at John F. Kennedy Space Center provides a test bed for bioregenerative studies using plants to provide food, oxygen, carbon dioxide removal, and potable water to humans during long term space travel. Growing plants in enclosed environments has brought about concerns regarding the level of volatile organic compounds (VOCs) emitted from plants and the construction materials that make up the plant growth chambers. In such closed systems, the potential exists for some VOCs to reach toxic levels and lead to poor plant growth, plant death, or health problems for human inhabitants. This study characterized the air in an enclosed environment in which wheat cv.Yocora Rojo was grown. Ninty-four whole air samples were analyzed by gas chromatography/ mass spectrometry throughout the eighty-four day planting. VOC emissions from plants and materials were characterized and quantified.

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ACKNOWLEDGMENTS

This research was conducted under the direction of Dr. William M. Knott, Chief, Biological Research and Life Support Office, John F. Kennedy Space Center, Florida. The authors and the Bionetics Coorporation thank the NASA Life Sciences Division for their continued support of the CELSS research program at John F. Kennedy Space Center. We thank Hassan Patterson for drawing the chemical structures shown in Table 3.

PRODUCT DISCLAIMER

This report may not be used to imply the endorsement by NASA or by NASA employees of a commercial product or process.

The emphasis of NASA's Controlled Ecological Life Support System (CELSS) program is to use plants to provide food, oxygen, potable water, and carbon dioxide removal to humans during long term space travel. In order to study the feasibility of growing plants in enclosed environments, the Biomass Production Chamber (BPC) was designed and constructed at Kennedy Space Center (Averner,1989;Prince and Knott,1989). The Biomass Production Chamber is a two-level chamber that is 3.5 m in diameter and 7.5 m high. Each level of the chamber has two plant growth shelves that hold 16 hydroponic trays each (Prince et al.,1987). A total of 20 m^2 is available to grow plants. The BPC is equipped with air conditioning, heating, ventilation, atmospheric, lighting, and nutrient delivery control (Sager et al.1988).

Construction materials used in the BPC include steel, plastics and polymers, such as polyvinyl chloride (PVC), chlorinated polyvinyl chloride (CPVC), acrylonitrile-butadiene-styrene (ABS plastic), acrylic resin products, Polytetrafluoroethylene (Teflon™), Vinylidene fluoride hexafluoropropylene copolymer (Viton™), polypropylene, and polyethylene. Other materials that are used as sealants in the BPC include Dow Corning sealants RTV 3045 and 3040, as well as other silicone caulking compounds. Many of these materials slowly emit volatile organic compounds (VOCs) into the surrounding air. Determination of the identity and concentration of volatiles emitted from materials and plants in the enclosed environment is essential as many of these compounds have been linked to phytotoxicity, poor growth rates and death in some plants. Toxic levels of ethylene and ethane have been reported to evolve from polyethylene, polypropylene, and clear PVC (Scott and Wills,1972). Xylene, a solvent that is emitted as paint dries, has been shown to be harmful to plants (Tibbitts et al.,1977). Silicone elastomers have been reported to emit cyclohexylamine and cause damage in barley, cucumbers, and tomatoes (Pezet and Grindrat, 1978). Phthalates emitted from plastics have been associated with injury and death of cabbage plants (Hardwick et al., 1984).

The materials in the BPC are not the only source of volatile compounds in the air; the plants also contribute to the total VOCs into the air. For example, (E)-2-Hexenal was among the 25 volatile compounds that have been associated with wheat plants (Buttery et al.1985). Aliphatic hydrocarbons and terpenoids were found to be the dominant class of compounds from headspace analysis of chickpeas (Rembold et al.1989). Nonanal was found to be a major volatile component from wheat (Hamilton-Kemp and Anderson,1984).

The BPC provides a unique environment in that it can be sealed and the levels of the VOCs can be monitored over extended periods of time. The atmospheric study conducted during wheat cv.Yorcora Rojo production (BWT931) in the BPC had two objectives: the first was to determine the types and concentration of products emitted from the BPC materials and plants and, the second to determine the effectiveness of a charcoal/Purafil™ filtering system for removing both biogenic and anthropogenic products from the air.

EXPERIMENTAL METHODS

Charcoal/Purafil™ filters were placed in the upper level of the BPC while the lower level was the unfiltered control. The charcoal filters were 150% by weight activated carbon embedded on polyester (406 g fabric weight with 609 g carbon per m^2 , from Lewcott Corp.) (Heath and Manukian,1993). Eight 30.5 cm x 45.7 cm x 1.5 cm charcoal filters were used. The Purafil™ is a chemisorbant of potassium permanganate on an activated alumina substrate. These pellets selectively remove unsaturated hydrocarbons by controlled oxidation. Two kilograms of this material were used in the filtered level of the BPC. The filters were placed so that they were exposed to ambient air (the air was not forced to circulate through them). The Purafil™ was not replaced throughout the entire planting; however, charcoal filters were replaced on the 55th day after planting .

Wheat (*Triticum aestivum* cv.Yecora Rojo) plants for the study were grown from seed to maturity in .025 m^2, vacuum-formed trays (Mackowiak et al,1989). A total of 64 trays was used for the study. Essential nutrients and water were provided using a recirculating nutrient film culture, with nutrient solution pH and electrical conductivity automatically maintained near 5.8 and 0.12 S m^{-2}, respectively. Air temperatures were maintained at 24°C in the light and 20°C in the dark for the first 10 days, after which temperatures were cycled at 24°C (light) and 16°C (dark). Lighting was provided by 96 high-pressure sodium lamps and cycled to provide 20 h light and 4 h dark each 24 h period. Irradiance at the top of the plant canopy averaged 750 mol m^{-2} s^{-1} photosynthetic photon flux throughout growth. Relative humidity was controlled to 75% (1.76 kPa absolute) and carbon dioxide concentration to 0.10 ppm (0.10 kPa) during the light period.

Ninty-four air samples from 36 different days were collected and analyzed periodically throughout the 84 days of planting. Duplicate samples were collected from the filtered chamber. Samples were collected between 0730 hrs and 0830 hrs each morning, approximately 2 hours after the lights came on each day.

The air samples (16L) were collected in previously tested clean, passivated canisters (SUMMA[R] polished stainless steel). The canisters and pumping system were checked for cleanliness and background levels by filling the canisters with ultra pure nitrogen and analyzing the nitrogen in the same manner as described for air analysis. The air was analyzed according to modified EPA method TO14 (Stephens and Myron, 1990). Using the Tekmar LSC 2000/2016, 10 L of the air sample were passed across an adsorbent trap (VOCARB 4000 from Supelco). The volatile organic compounds in the sample were adsorbed onto the trap. The trap was then heated and the volatiles desorbed. A Tekmar Capillary Interface model 142530-000 cryogenically focused the volatile compounds at the gas chromatograph/ transfer line interface. The compounds were separated with a Hewlett Packard Series II model 5890 gas chromatograph. The analytical columns used were a J&W DB1 30 m x 0.596 mm with a 3 um film thickness (first 20 days) and a J&W 624 30 m x 0.596 mm with a 3 um film thickness (last 64 days). The gas chromatograph was interfaced to a Hewlett Packard Model 5970 mass selective detector (MSD).

Standards were prepared from dilutions of VOC kits from Supelco and neat chemicals from Aldrich, Sigma, and ChemService. Continuing calibration standards were run daily so that compensation could be made for any fluctuations that occur within the system. Five-point calibration curves ranging from 10 to 100 ng on column were used to ascertain that the components were quantified in a linear manner. Table 1 lists the standards used, the quantifiable detection limits, and vendor. The quantifiable limits are calculated on a basis of a ratio of ion abundance of the compound of interest and its concentration to ten times the abundance of baseline noise signal. Detectable limits are defined as three times the signal/noise ratio. An estimation of concentration of compounds for which standards were not available was achieved by comparison to the response of a standard that had similar organic functional groups.

Data analysis was achieved using Target software for UNIX from Hewlett Packard. The software provided library searching for qualitative data analysis and statistical analysis for quantification.

RESULTS

Labeled chromatograms of the filtered and unfiltered air from the BPC on days 15, 44, and 82 of the planting are shown in Figures 1 through 6. Each peak of the chromatogram represents a compound found in the air, while the area under the peak indicates the concentration of the compound. The chromatograms illustrate the changes in the composition of the air over the planting as well as the similarities and differences in the filtered and unfiltered air. The abundance on the Y-axis of the chromatograms in Figures 1 and 4 is corrected to account for a relative change as a result of voltage adjustments in the photomultiplier in the MSD.

Emissions from the construction materials, plants, and unknown sources (possibly microbial or mold) were detected in the air samples. The origin of the emissions was determined by separate headspace analyses of the materials and the plants at various stages of their development (unpublished data not shown). Table 2 lists average concentration, the number of days detected, and suspected origin of each compound. The data show that 33% of the compounds result from emissions from materials and solvents, 37% are emitted from the wheat and, 30% are from unknown sources. Eighty-two percent of the total concentration of volatiles in the BPC are from the materials, 12% are emitted from the wheat, and 6% are from unknown sources. The weighted-average concentration of VOCs is greater in the unfiltered BPC. The concentration is 19% greater for volatiles emitted from materials, 87% greater from wheat, and 29% greater from unknown sources. Over all, the weighted concentration of VOCs was 26% greater in the unfiltered BPC. Table 3 shows the structures of some of the more prevalent compounds found in the BPC.

The concentrations of volatile compounds that have been traced to BPC construction materials and solvents are represented in Figures 7 through 22. The concentrations have been plotted by day after planting. The graphs of the volatiles from material sources follow two patterns, either the concentrations are high early in the study and decrease with time, or the concentration remains constant throughout the planting. Some examples of volatiles that are higher in concentration early in the planting are tetrahydrofuran (Figure 14), toluene (Figure 15) and hexane (Figure 11). This could indicate that after a period of time, the off-gassing from materials reaches an equilibrium. Dichloromethane (Figure 8) is an example of a compound whose concentration remained fairly constant throughout the planting.

The concentrations of each volatile compound that has been traced to biogenic emissions from plants are represented in Figures 23 through 32. The graphs were generated by plotting the concentration by day after planting. The concentration of volatile compounds emitted from plants tended to peak either between days 35 to 42 of the planting, or toward the end of the planting. Day 35 to 42 of the planting coincides with heading and anthesis of the plants. Some of the compounds that behaved this way were the hexanal (Figure 27), heptanal (Figure 28), and nonanal (Figure 29).

The increase in concentrations toward the end of the planting could be attributed to the maturation and ripening of the wheat and subsequent decay of the plant matter, or possibly the greater biomass of the wheat. Dimethylaminoacetonitrile (Figure 30), tetramethylurea (Figure 32) and tetramethylthiourea (Figure 31) are examples of compounds that behaved in this way. Methylfuran was detected in the BPC on day 35 of the planting, at which time the wheat heads first appeared. Headspace analysis of the wheat heads and other wheat parts indicated that 2-methylfuran (Figure 23) was emitted from the heads only.

The graphs of compounds whose sources are currently unknown can be seen in Figures 33 through 37. The graph patterns of benzothiazole (Figure 33) and benzaldehyde (Figure 34) suggest that these compounds are not detected early in the planting. This could indicate that these compounds were emitted from a mold that developed around the bases of wheat culms later in growth. The graph of the concentration of phenol (Figure 35) plotted by day-after-planting seems to follow a pattern similar to the compounds associated with construction materials.

Low molecular weight alkenes such as ethylene, pentadiene, 2-methylpropene (Figure 36) and 2,2,4-trimethyl-1-pentene (Figure 38) are less concentrated or absent in the filtered BPC (Peterson,in press). This indicates that the Purafil™ filters are effective at removing this class of compounds. The presence of 2,2,4-trimethylpentene in the filtered BPC late in the planting may indicate that the Purafil™ was near saturation.

The charcoal filters were most effective at decreasing the concentration of some of the siloxane compounds. This is illustrated in Figures 16-20. Early in the planting the concentrations of these compounds were relatively low; the concentrations generally increased after 12 days of planting. The filters were replaced on day 60 of the planting and the concentrations of the siloxanes decreased markedly. In each case the concentrations increased slowly following the decrease after the filters were replaced.

The concentration of chlorinated compounds in the BPC air was erratic. This could be attributed to the presence of these compounds in the ambient air in the area outside the BPC (unpublished data). The Purafil™ and charcoal filters had little effect on the concentration of these compounds, as the concentration of these compounds was 25% greater in the filtered BPC. The graphs of the concentrations of these compound by day-after-planting can be seen in Figures 7 through 9.

CONCLUSIONS

The goals of the total air analysis of wheat study BWT931 were to determine the identities and concentrations of the compounds detected in the BPC and to determine the effectiveness of the filter system. The results led to the following conclusions:

* The majority (82%) of the total concentration of the compounds in the BPC air was emitted from construction materials.

* The filter system used in the BPC was moderately effective at removing the VOCs from the air. The concentration of VOCs was 26% greater in the unfiltered BPC.

The concentration of VOCs in plant production chambers for a CELSS could be reduced (in future chambers) by reducing the amount of construction materials that emit VOCs. In addition, the filter system could be improved by placing the filter into the air handling system so that the air would be forced to pass through it, by changing the filters at regular intervals (bi-weekly), and by using a larger area/volume ratio filter.

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Table 1. List of Standards Used to Determine the Concentration of Compounds Detected in the BPC Air with Quantifiable Detection Limit and Vendor.

Compound	QDL (ug/m^3)	Vendor
Benzene	0.52	Supelco
Benzaldehyde	0.21	ChemServ.
Benzothiazole	0.61	ChemServ.
Bromobenzene	0.65	Supelco
Bromochloromethane	2.44	Supelco
Bromodichloromethane	0.96	Supelco
Bromomethane	0.68	Supelco
n-Butylbenzene	0.18	Supelco
sec-Butylbenzene	0.74	Supelco
tert-Butylbenzene	0.21	Supelco
2-Butoxyethanol	1.10	Aldrich
2-(2-Butoxyethoxy)ethanol	1.10	Aldrich
CFC 113 (FREON 113[R])	0.38	Supelco
Carbon disulfide	0.38	EM
Carbon tetrachloride	0.79	Supelco
trans-Caryophyllene	0.32	Sigma
Chlorobenzene	0.33	Supelco
Chloroethane	3.03	Supelco
Chloroform	0.67	Supelco
Chloromethane	14.43	Supelco
2-Chlorotoluene	0.25	Supelco
Dibromochloromethane	1.16	Supelco
1,2-Dibromoethane	1.43	Supelco
1,2-Dichlorobenzene	0.87	Supelco
1,3-Dichlorobenzene	0.35	Supelco
1,4-Dichlorobenzene	0.32	Supelco
Dichlorodifluoromethane	7.65	Supelco
1,2-Dichloroethane	2.67	Supelco
1,1-Dichloroethene	1.92	Supelco
cis-1,2-Dichloroethene	1.19	Supelco
trans-1,2-Dichloroethene	1.47	Supelco
Dichloromethane	2.29	Supelco
1,2-Dichloropropane	2.84	Supelco
1,3-Dichloropropane	1.33	Supelco
1,1-Dichloropropene	1.22	Supelco
cis-1,3-Dichloropropene	1.19	Supelco
trans-1,3-Dichloropropene	1.77	Supelco
2,6-Di-tert-butyl-p-cresol	1.21	Aldrich
2,6-Di-tert-butyl-2,5-cyclohexadiene -1,4-dione	1.11	Aldrich
Dimethyldisulfide	0.21	Aldrich
Ethylbenzene	0.21	Supelco
2-Ethyl-1-hexanol	1.03	ChemServ.
Hexachlorobutadiene	0.54	Supelco
Hexamethylcyclotrisiloxane	0.46	Aldrich
Hexanal	0.85	Aldrich
trans-2-Hexenal	9.46	Aldrich

Table 1. Continued

Compound	QDL (ug/m^3)	Vendor
cis-3-Hexen-1-ol	115.00	Aldrich
Humulene	0.98	Sigma
Isoprene	1.64	Aldrich
Isopropylbenzene	0.18	Supelco
Limonene	3.05	ChemServ.
2-Methylfuran	1.72	Aldrich
Naphthalene	2.38	Supelco
Nonanal	0.18	Aldrich
Octamethylcyclotetrasiloxane	0.19	Aldrich
Pinene, alpha-	0.54	ChemServ.
Pinene, beta-	0.58	ChemServ.
n-Propylbenzene	5.44	Supelco
Styrene	0.41	Supelco
Terpinene	0.68	Aldrich
1,1,1,2-Tetrachloroethane	0.90	Supelco
1,1,2,2-Tetrachloroethane	2.45	Supelco
Tetrachloroethene	0.39	Supelco
Tetrahydrofuran	1.01	ChemServ.
Tetramethylurea	4.41	Aldrich
Tetramethylthiourea	3.71	Aldrich
Toluene	0.31	Supelco
1,2,3-Trichlorobenzene	0.70	Supelco
1,2,4-Trichlorobenzene	0.55	Supelco
1,1,1-Trichloroethane	0.78	Supelco
1,1,2-Trichloroethane	0.70	Supelco
Trichloroethene	0.45	Supelco
Trichlorofluoromethane	0.31	Supelco
1,2,3-Trichloropropane	5.58	Supelco
1,2,4-Trimethylbenzene	0.25	Supelco
1,3,5-Trimethylbenzene	12.40	Supelco
o-Xylene	0.62	Supelco
m-Xylene	0.51	Supelco
p-Xylene	0.51	Supelco

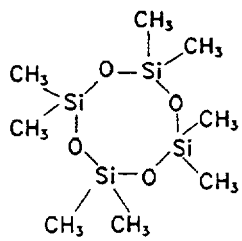
Table 2. VOCs Detected in Filtered and Unfiltered BPC Air With Average Concentration (ug/m^3), Number of Days Present, and Source.

Compound	Filtered Air		Unfiltered Air		Source
	AVG	DAY	AVG	DAY	
1,1,1,5,5,5-Hexamethyl-trisiloxane	4.4	26	8.6	6	Materials
1,1,1-Trichloroethane	27.4	29	10.3	35	Solvent
1,1,2-Trichloro-1,2,2-trifluoro-ethane	4.7	34	6.3	30	Solvent
1,1-Dichloroethene	31.3	19	46.8	22	Solvent
1,2,4-Trimethylcyclohexane	.2	1	.4	2	Solvent
1,2-Dichloro-1,1,2,2-tetrafluoro-ethane	2.7	6	6.5	8	Solvent
1,2-Dichloroethene	18.5	3	2.1	3	Solvent
1,2-Dichloropropane	-	-	2.4	2	Solvent
1.2-Dimethylcyclohexane	6.7	11	.3	1	Unknown
1,6-Dichloro-1,5-cyclooctadiene	1.8	16	2.1	10	Materials
1-Butanol	.4	24	.4	23	Wheat
2,6-Di-tert-butyl-p-cresol	90.8	30	86.7	27	Materials
2,6-Di-t-Butyl-2,5-cyclohexadiene-1,4-dione	6.7	23	4.6	24	Materials
2-(2-Butoxyethoxy)ethanol	1.1	22	1.0	28	Solvent
2-Butanone	.5	2	.7	1	Wheat
2-Butyl-1-octanol	.4	1	-.	-	Unknown
2-Butoxyethanol	1.1	29	1.1	25	Solvent
2-Ethyl-1-hexanol	.2	30	.1	24	Wheat
2-Ethylfuran	-	-	.1	1	Wheat
2-Ethylpyridine	-	-	.3	1	Unknown
2-Heptanone	-	-	2.0	2	Wheat
2-Methyl-1-propene,trimer	-	-	1.4	13	Unknown
2-Methylbutadiene	-	-	.1	1	Wheat
2-Methylbutane	2.7	21	2.5	29	Wheat
2-Methylfuran	.5	23	.9	23	Wheat
2-Methylpropene	-	-	8.2	25	Unknown
2-Pentylfuran	-	-	1.4	1	Wheat
2-Propanol	11.9	1	-.	-	Wheat
2-Propanone	.5	1	-.	-	Wheat
3-Cyclohexene-1-carbonitrile	1.0	21	1.1	11	Unknown
3-Hexen-1-ol	-	-	.2	1	Wheat
3-Methyl-1-butanol	-	-	.5	1	Wheat
3-Methylfuran	.5	8	.8	18	Wheat
4-Butoxy-1-butanol	-	-	.1	1	Wheat
4-Methylbenzamine	.6	7	.7	7	Unknown
4-Pyridinemethanol	-	-	.5	1	Unknown
Acetic Acid	1.1	2	2.3	2	Unknown
Benzaldehyde	15.3	26	23.9	26	Unknown
Benzenemethanol	1.1	2	.8	5	Unknown
Benzothiazole	28.6	22	26.8	23	Unknown
Bromochloromethane	-	-	.9	1	Unknown
Bromomethane	14.9	2	.7	2	Solvent

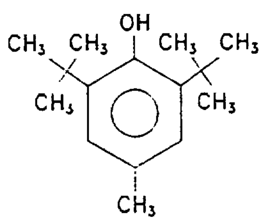
Table 2. Continued

Compound	Filtered Air AVG	Day	Unfiltered Air AVG	Day	Source
Butane	37.8	20	7.4	5	Generator
C9+Alkanes	-	-	14.9	31	Materials
Carbon disulfide	5.2	10	9.6	9	Wheat
Chlorodifluoromethane	104	29	75.2	35	Solvent
Cyclohexane	-	-	.5	1	Unknown
Cyclohexanone	1.6	4	.7	1	Unknown
Decamethylcyclopentasiloxane	20.9	35	16.9	35	Materials
Decanal	-	-	1.3	1	Wheat
Dichlorobenzene	1.9	17	1.9	4	Materials
Dichlorodifluoromethane	12.4	2	18.2	1	Materials
Dichloromethane	94.4	33	169.	32	Materials
Dimethylaminoacetonitrile	.9	16	.3	20	Wheat
Dimethylbenzene	2.2	11	2.4	9	Materials
Dimethylcyclohexane	-	-	.3	1	Unknown
Dimethyldisulfide	4.7	3	-.	-	Wheat
Dodecamethylcyclohexasiloxane	37.3	34	11.3	34	Materials
Dodecane	5.9	1	1.1	1	Unknown
Ethanol	2.5	2	-.	-	Wheat
Ethylbenzene	.8	1	.9	6	Unknown
Ethylidene-cyclopropane	-	-	.1	1	Unknown
Furan	-	-	30.5	10	Wheat
Heptanal	.2	15	.3	20	Wheat
Hexamethyocyclotrisiloxane	25.9	36	34.1	36	Materials
Hexanal	.2	19	.2	13	Wheat
Hexane	3.8	23	4.2	28	Materials
Methylcyclopentane	-	-	.2	2	Unknown
Methyl ester octanoic acid	4.2	1	-.	-	Wheat
Methyl ester nonanoic acid	5.6	1	-.	-	Wheat
Methyl ester dodecanoic acid	5.1	1	-.	-	Wheat
N,N-Dimethylformamide	1.1	4	1.3	6	Wheat
N-Ethyl-N-methyl-1-propamine	2.11	4	.6	2	Wheat
Napthalene	-	-	1.3	2	Materials
Nonanal	.1	22	.8	21	Wheat
Nonane	-	-	1.2	1	Unknown
Octamethylcyclotetrasiloxane	13.4	36	19.3	36	Wheat
Pentane	12.2	30	12.7	29	Wheat
Phenol	11.9	22	15.5	22	Unknown
Tert.Butyl isothiocynate	1.2	16	.4	4	Unknown
Tetrachloroethene	2.5	5	.2	2	Solvent
Tetrahydrofuran	134	35	149.	35	Materials
Tetramethylthiourea	.6	13	.4	16	Wheat
Tetramethylurea	3.2	17	2.8	19	Wheat
Thieno[2,3-c]pyridine	-	-	.2	1	Unknown
Thiobismethane	2.5	3	3.3	6	Wheat
Thiourea	9.3	20	14.1	16	Wheat
Toluene	3.3	37	4.6	37	Materials
Trichlorofluoromethane	3.6	28	3.4	28	Solvent

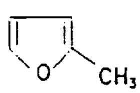
Table 3. Structures of Compounds Detected in BPC Air.



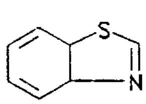
Octamethylcyclotetrasiloxane



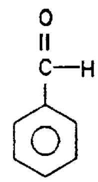
2,6-Di-tert-butyl-p-cresol



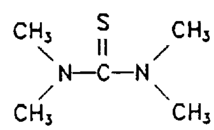
2-Methylfuran



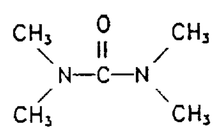
Benzothiazole



Benzaldehyde



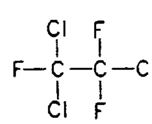
Tetramethythiourea



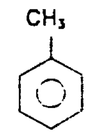
Tertramethylurea

$HO-CH_2\ CH_2\ -O-C_4\ H_9$

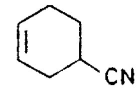
2-Butoxyethanol



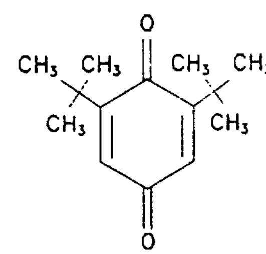
1,1,2-Trichloro-1,2,2-trifluoroethane



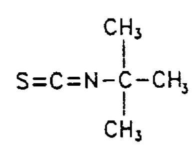
Toluene



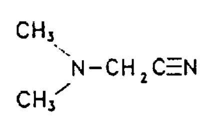
3-Cyclohexene-1-carbonitrile



2,6 Di-tert-butyl-2,5-cyclohexadiene-1,4-dione



Tert-Butyl-isothiocyanate



Dimethylaminoacetonitrile

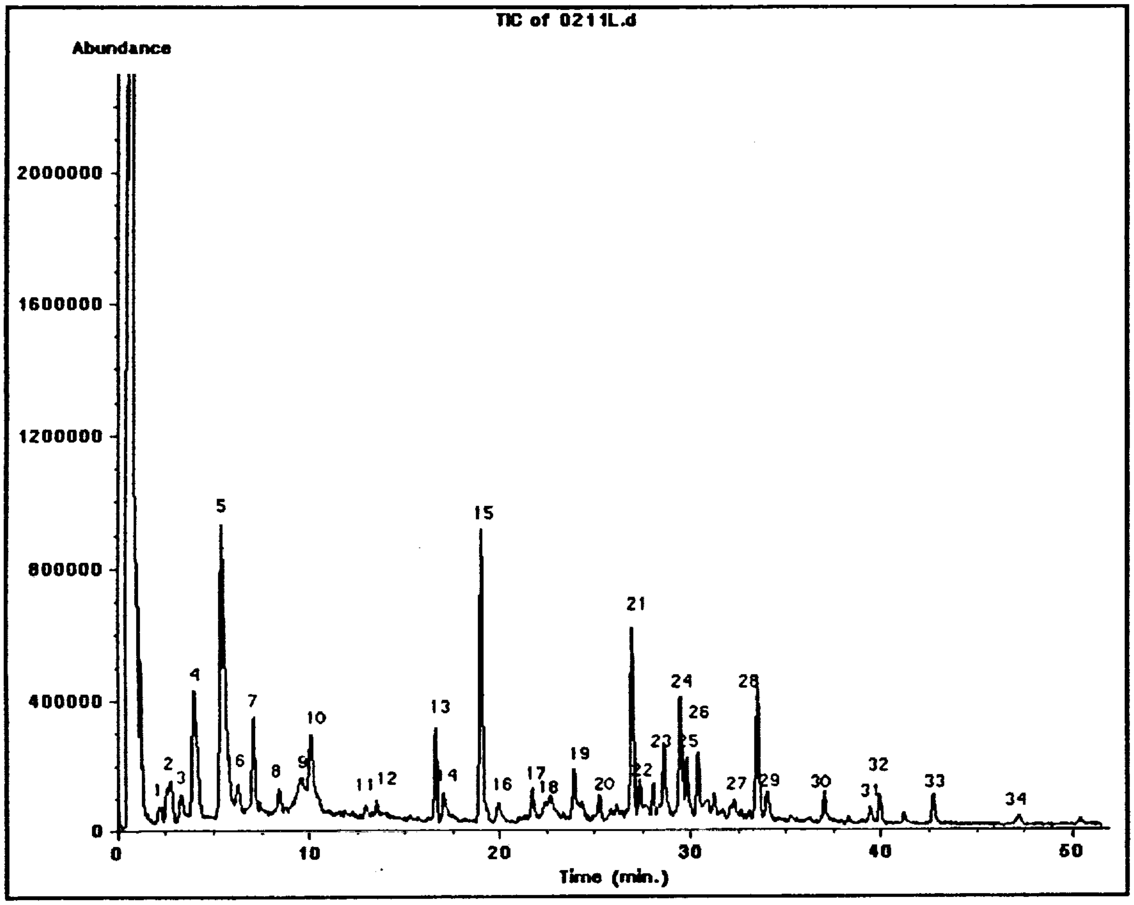


Figure 1. Total Ion Chromatogram (Corrected Abundance) of 10 liters of Unfiltered BPC Air on Day 15 of Wheat Study BWT931.

Peak Number	Compound
1	2-Methylbutane
2	Trichlorofluoromethane
3	Unknown
4	1,1,2-Trichloro-1,1,2-trifluoro ethane and Carbon disulfide
5	Dichloromethane
6	Hexane
7	Trimethylsilanol
8	Tetrahydrofuran
9	1,1,1-Trichloroethane
10	Cyclohexane
11	Alkane
12	1,1-Dichloropropane
13	Toluene
14	Acetic acid
15	Hexamethylcyclotrisiloxane
16	Hexanal
17	1,4-dimethylbenzene

Peak Number	Compound
18	2-Butoxoethanol
19	1,2,3-Trimethylbenzene
20	Alkane
21	Octamethylcyclotetrasiloxane
22	2-Methylpropene,trimer
23	Alkane
24	Tetramethylurea
25	Alkane
26	Hexylpentylether
27	Dodecane
28	Decamethylcyclopentasiloxane
29	Alkane
30	2-(2-Butoxyethoxy)ethanol
31	Tetramethylthiourea
32	Dodecamethylcyclohexasiloxane
33	1,6-Dichloro-1,5-cyclooctadiene
34	1,1,1,5,5,5-Hexamethyl-trisiloxane

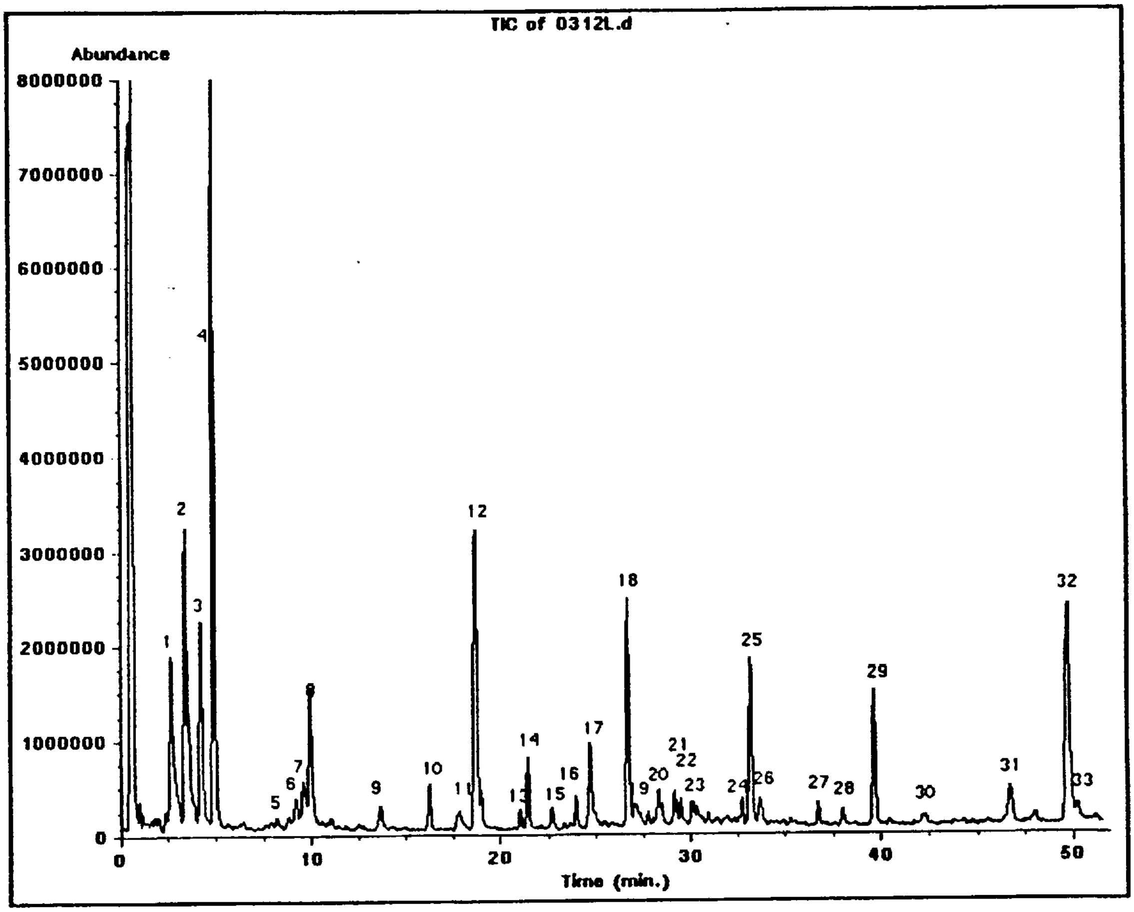


Figure 2. Total Ion Chromatogram of 10 Liters of Unfiltered BPC Air on Day 44 of Wheat Study (BWT931)

Peak Number	Compound
1	Trichlorofluoromethane
2	Carbon disulfide and 1,1,2-Trichloro-1,2,2-trifluoroethane
3	Thiourea and Unknown chlorinated compound
4	Dichloromethane
5	2-Methylfuran
6	Tetrahydrofuran
7	1,1,1-Trichloroethane
8	Trimethylsilanol
9	1-Butanol
10	Toluene
11	Dimethylaminoacetonitrile
12	Hexamethylcyclotrisiloxane
13	t-Butylisothiocyanate
14	1,4-Dimethylbenzene
15	Unknown
16	Heptanal
17	2-Butoxyethanol
18	Octamethylcyclotetrasiloxane

Peak Number	Compound
19	Benzaldehyde
20	Alkane
21	Alkane
22	Alkane
23	3-Cyclohexene-1-carbonitrile
24	Nonanal
25	Decamethylcyclopentasiloxane
26	Alkane
27	2-(2-Butoxyethoxy)ethanol
28	Benzothiazole
29	Dodecamethylcyclohexasiloxane
30	1,6-Dichloro-1,5-cyclooctadiene
31	1,1,1,5,5,5-Hexamethyltrisiloxane
32	2,6-Di-tert-butyl-p-cresol
33	Unknown

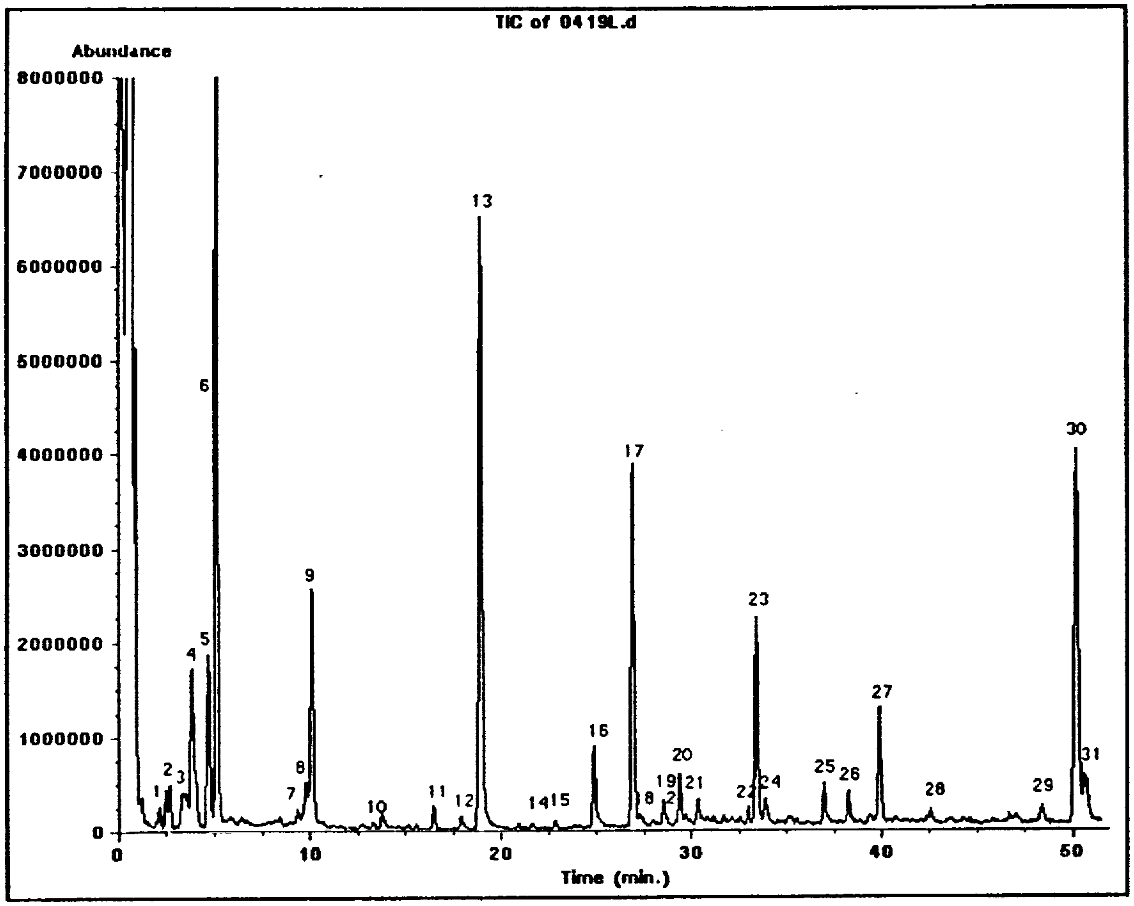


Figure 3. Total Ion Chromatogram of 10 Liters of Unfiltered BPC Air on Day 82 of Wheat Study BWT931.

Peak Number	Compound
1	Methylbutane
2	Trichlorofluoromethane
3	Pentane
4	1,1,2-Trichloro-1,2,2-trifluoroethane and Carbon disulfide
5	Thiourea and unknown chlorinated compound
6	Dichloromethane
7	Tetrahydrofuran
8	1,1,1-Trichloroethane
9	Trimethylsilanol
10	1-Butanol
11	Toluene
12	Dimethylaminoacetonitrile
13	Hexamethylcyclotrisiloxane
14	t-Butylisothiocyanate
15	Unknown
16	2-Butoxyethanol
17	Octamethylcyclotetrasiloxane
18	Heptanal
19	Alkane
20	Tetramethylurea
21	2-Ethyl-1-hexanol
22	Nonanal
23	Decamethylcyclopentasiloxane
24	Unknown
25	2-(2-Butoxyethoxy)ethanol
26	Benzothiazole
27	Dodecamethycyclohexasiloxane
28	1,6-Dichloro-1,5-cyclooctadiene
29	2,6-Di-t-butyl-2,5-cyclohexadiene-1,4-dione
30	2,6-Di-tert-butyl-p-cresol
31	Unknown

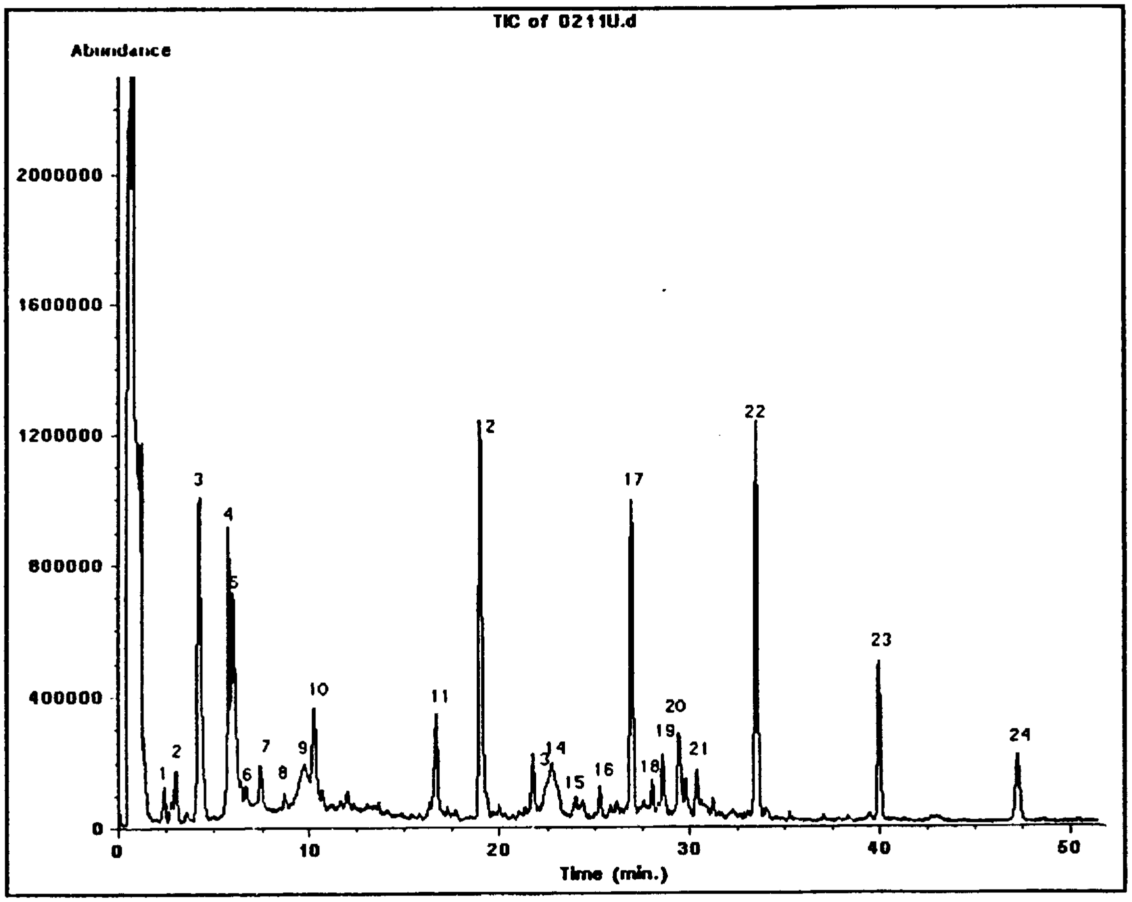


Figure 4. Total Ion Chromatogram (Corrected Abundance) of 10 Liters of Filtered BPC Air on Day 15 of Wheat Study BWT931

Peak Number	Compound
1	2-Methylbutane
2	Trichlorofluoromethane
3	1,1,2-Trichloro-1,2,2-trifluoro-ethane and Carbon disulfide
4	Dichloromethane
5	Dichloromethane
6	Hexane
7	Trimethylsilanol
8	Unknown
9	Tetrahydrofuran
10	1,1,1-Trichloroethane
11	Toluene
12	Hexamethylcyclotrisiloxane
13	1,4-Dimethylbenzene
14	2-Butoxyethanol
15	1,2,3-Trimethylbenzene
16	Benzaldehyde
17	Octamethylcyclotetrasiloxane
18	Alkane
19	Alkane
20	Tetramethylurea
21	3-Cyclohexene-1-carbonitrile
22	Decamethylcyclopentasiloxane
23	Dodecamethylcyclohexasiloxane
24	1,1,1,5,5,5-Hexamethylcyclo-trisiloxane

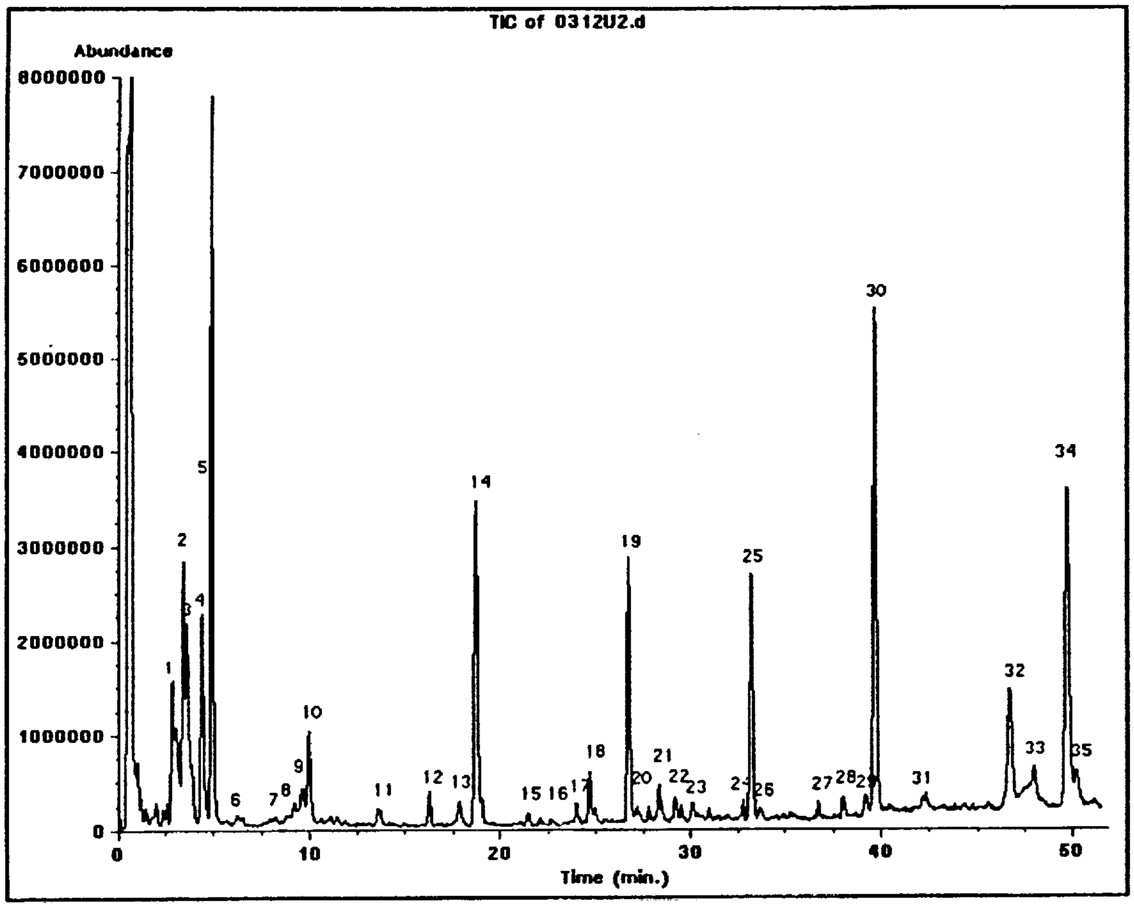


Figure 5. Total Ion Chromatogram of 10 Liters of Filtered BPC Air on Day 44 of Wheat Study BWT931.

Peak Number	Compound	Peak Number	Compound
1	Trichlorofluoromethane	19	Octamethylcyclotrisiloxane
2	1,1,2-Trichloro-1,2,2-trifluoro-ethane and Carbon disulfide	20	Benzaldehyde
3	1,1-Dichloroethene	21	Alkane
4	Thiourea and unknown chlorinated compound	22	Alkane
5	Dichloromethane	23	3-Cyclohexene-1-carbonitrile
6	Hexane	24	2-Methylbenzamine
7	2-Methylfuran	25	Decamethylcyclopentasiloxane
8	Tetrahydrofuran	26	Nonanal
9	1,1,1-Trichloroethane	27	2-(2-Butoxyethoxy)ethanol
10	Trimethylsilanol	28	Benzothiazole
11	1-Butanol	29	Unknown
12	Toluene	30	Dodecamethylcyclohexasiloxane
13	Dimethylaminoacetonitrile	31	1,6-Dichloro-1,5-cyclooctadiene
14	Hexamethylcyclotrisiloxane	32	1,1,1,5,5,5Hexamethyltrisiloxane
15	t-Butylisothiocyanate	33	2,6-Di-tert-butyl-2,5-cyclohexadiene-1,4-dione
16	Unknown	34	2,6-Di-tert-butyl-p-cresol
17	Heptanal	35	Unknown
18	2-Butoxyethanol		

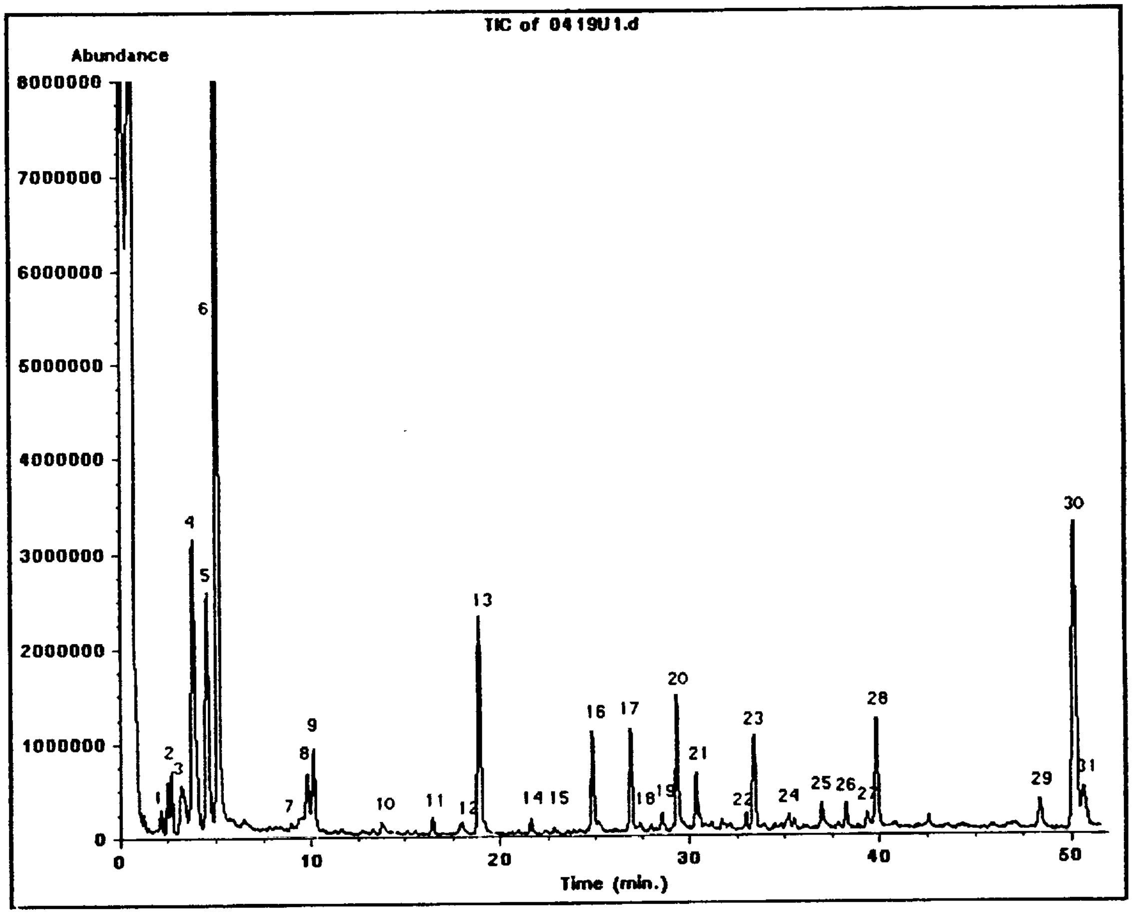


Figure 6. Total Ion Chromatogram of 10 Liters of Filtered BPC Air on Day 82 of Wheat Study BWT931.

Peak Number	Compound
1	2-Methylbutane
2	Trichlorofluoromethane
3	Pentane
4	1,1,2-Trichloro-1,2,2-trifluoro-ethane and Carbon disulfide
5	Thiourea and unknown chlorinated compound
6	Dichloromethane
7	Tetrahydrofuran
8	1,1,1-Trichloroethane
9	Trimethylsilanol
10	Butanol
11	Toluene
12	Dimethylaminoacetonitrile
13	Hexamethylcyclotrisiloxane
14	t-Butylisothiocyanate
15	Unknown
16	2-Butoxyethanol
17	Octamethylcyclotetrasiloxane
18	Heptanal
19	Alkane
20	Tetramethylurea
21	2-Ethyl-1-hexanol
22	Nonanal
23	Decamethylcyclopentasiloxane
24	Unknown
25	2-(2-Butoxyethoxy)ethanol
26	Benzothiazole
27	Tetramethylthiourea
28	Dodecamethylcyclohexasiloxane
29	2,6-Di-tert-butyl-2,5-cyclohexadiene-1,4-dione
30	2,6-Di-tert-butyl-p-cresol
31	Unknown

Figure 7. 1,1,1-Trichloroethane Concentrations-Wheat Study (BWT931)

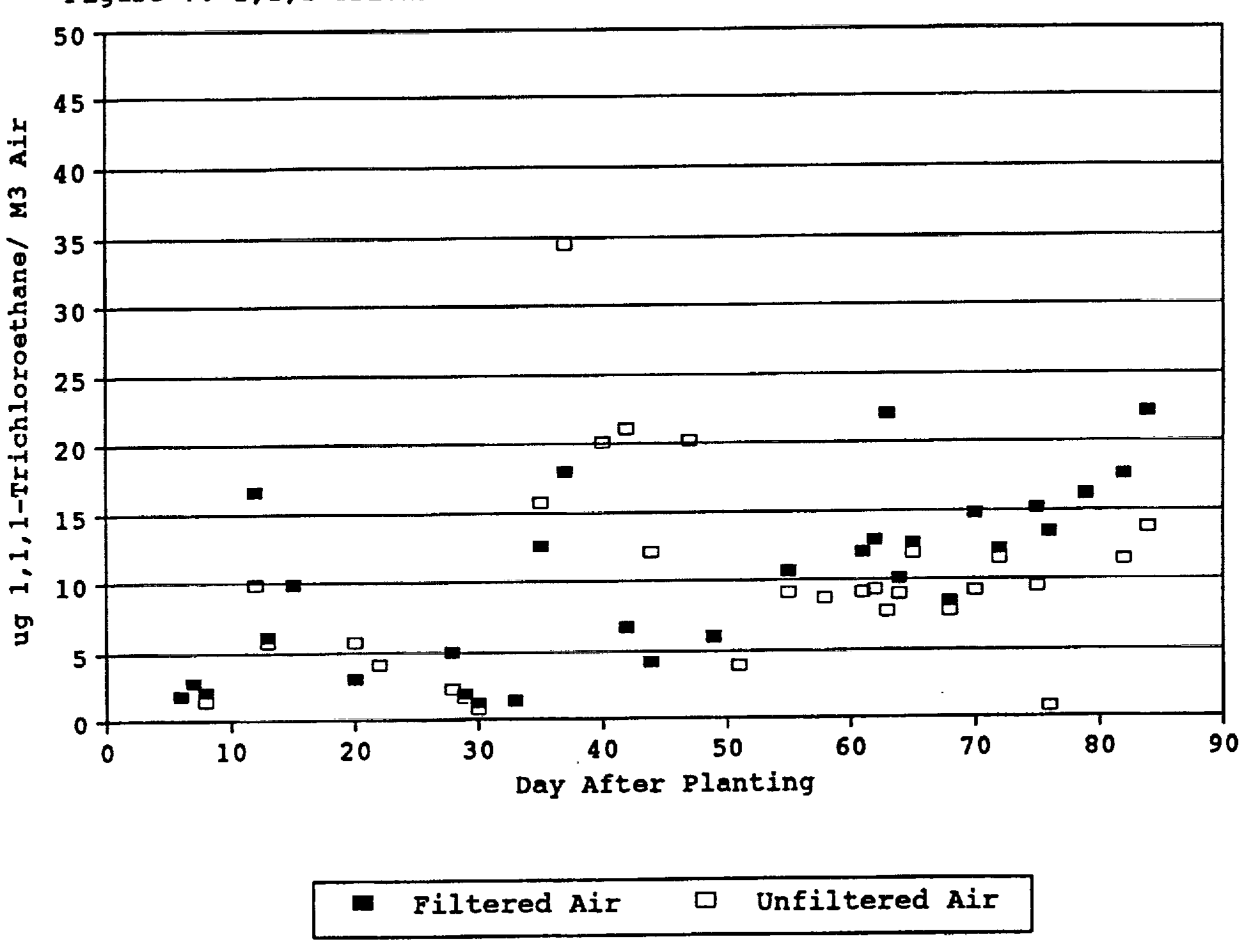


Figure 8. Dichloromethane Concentrations-Wheat Study (BWT931)

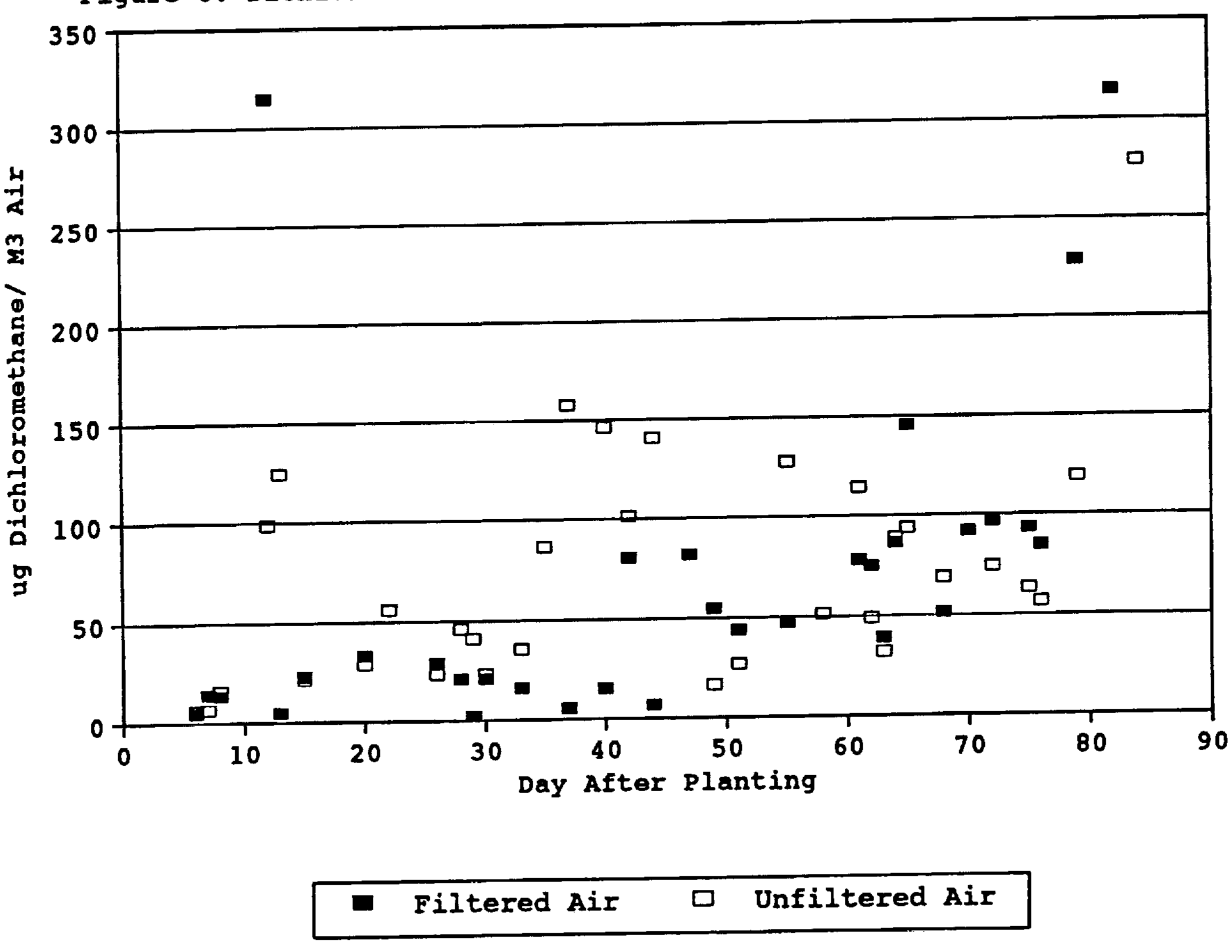


Figure 9. Chlorodifluoromethane Concentrations-Wheat Study (BWT931)

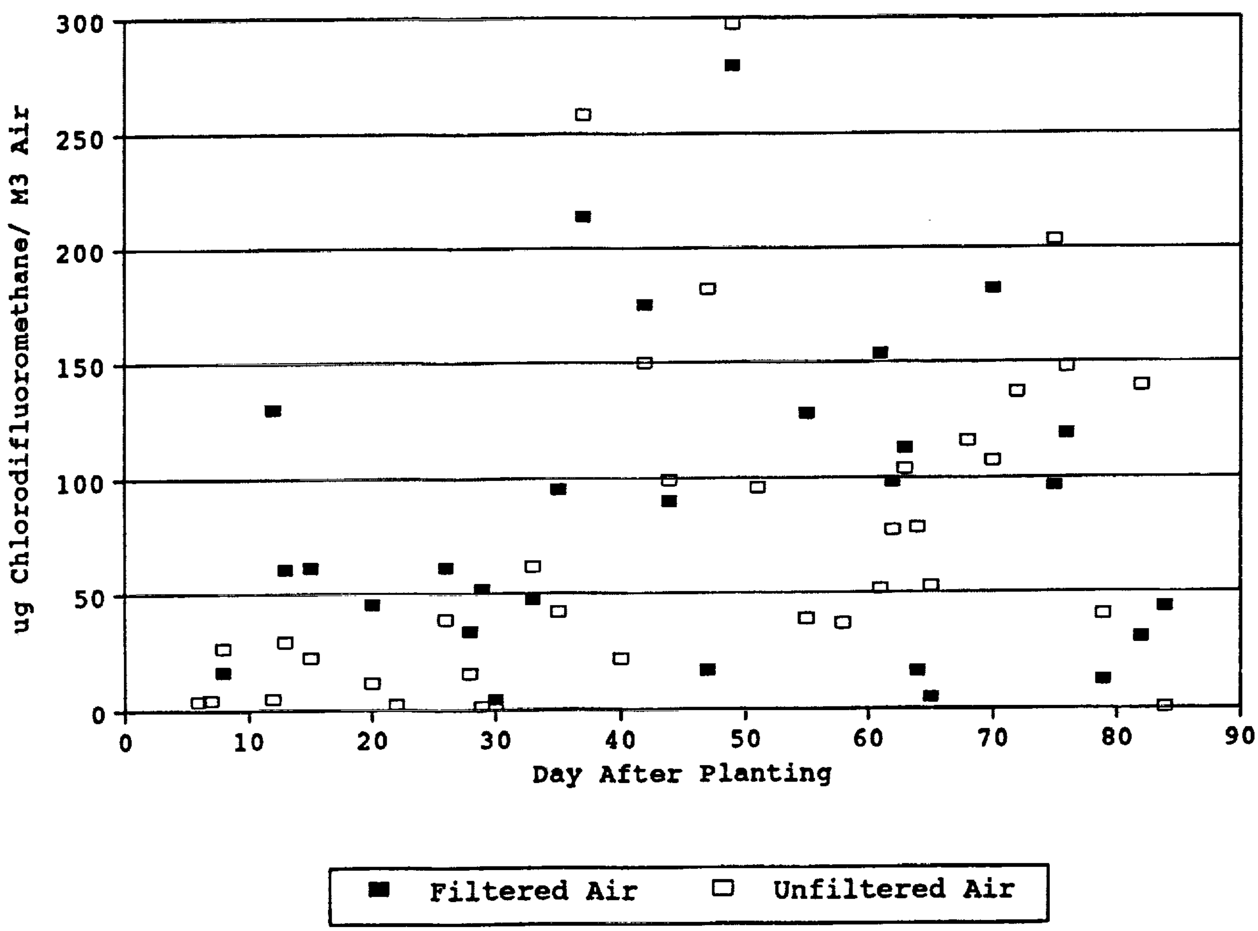


Figure 10. Pentane Concentrations-Wheat Study (BWT931)

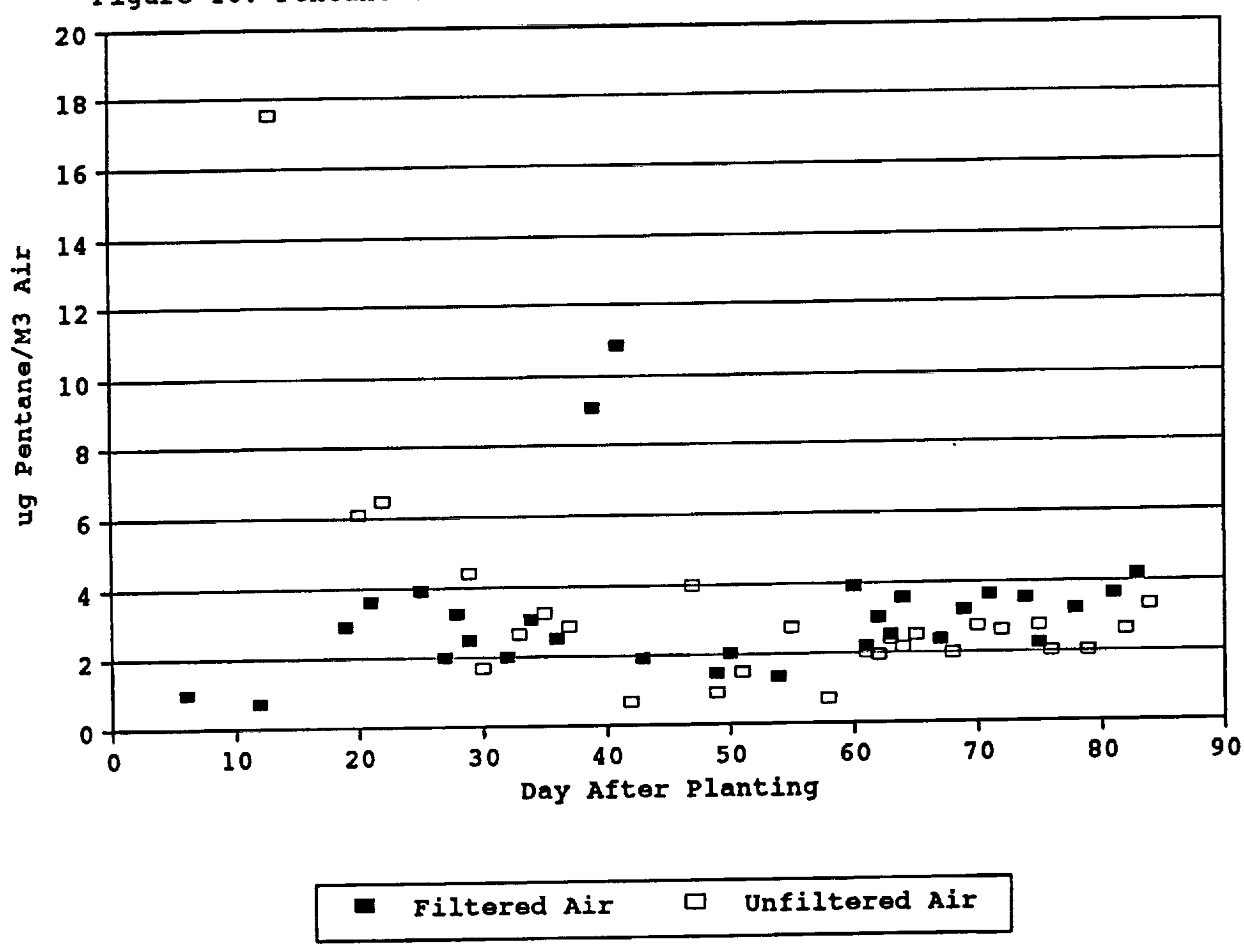


Figure 11. Hexane Concentrations-Wheat Study (BWT931)

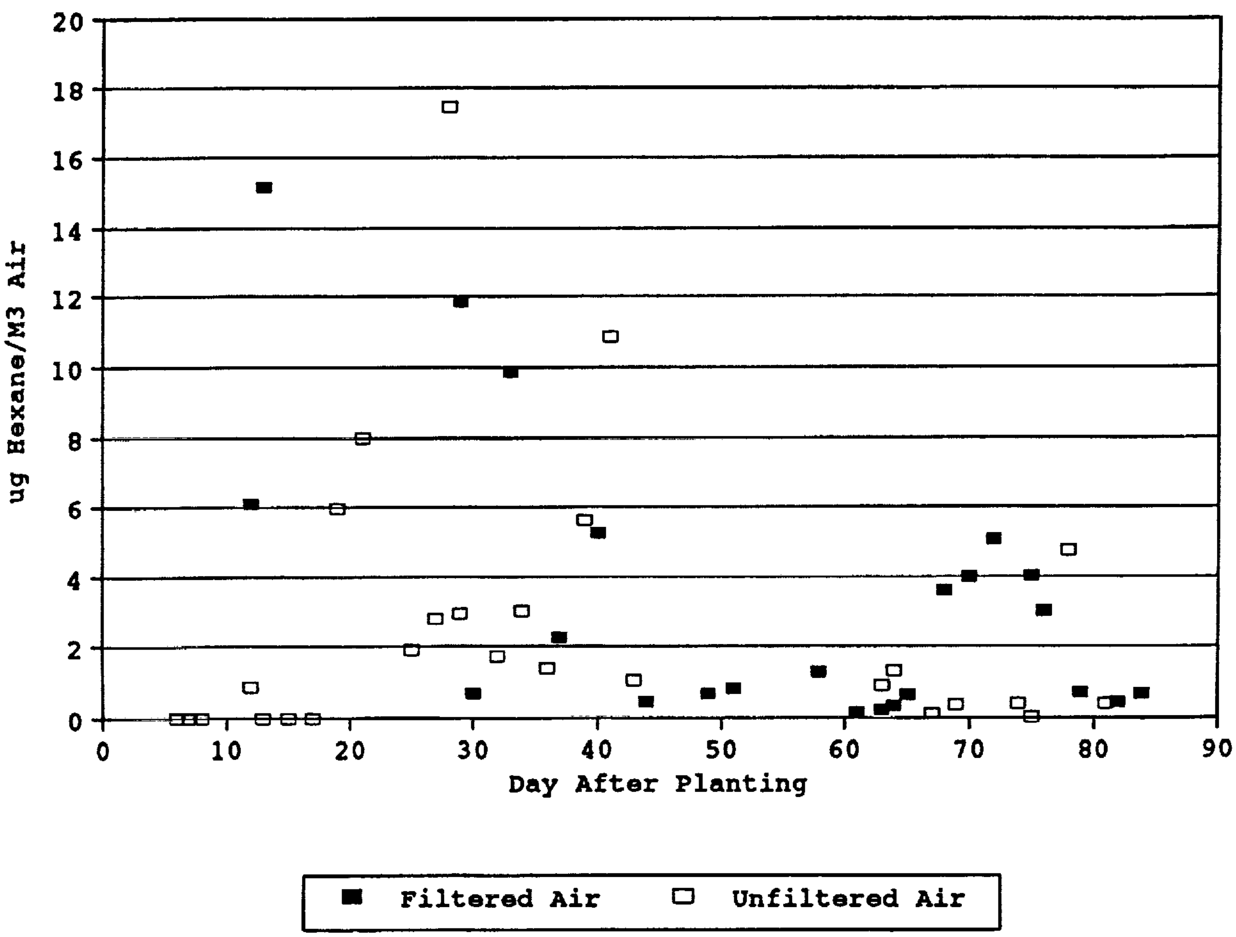


Figure 12. 2-(2-Butoxyethoxy)ethanol Concentrations-Wheat Study(BWT931)

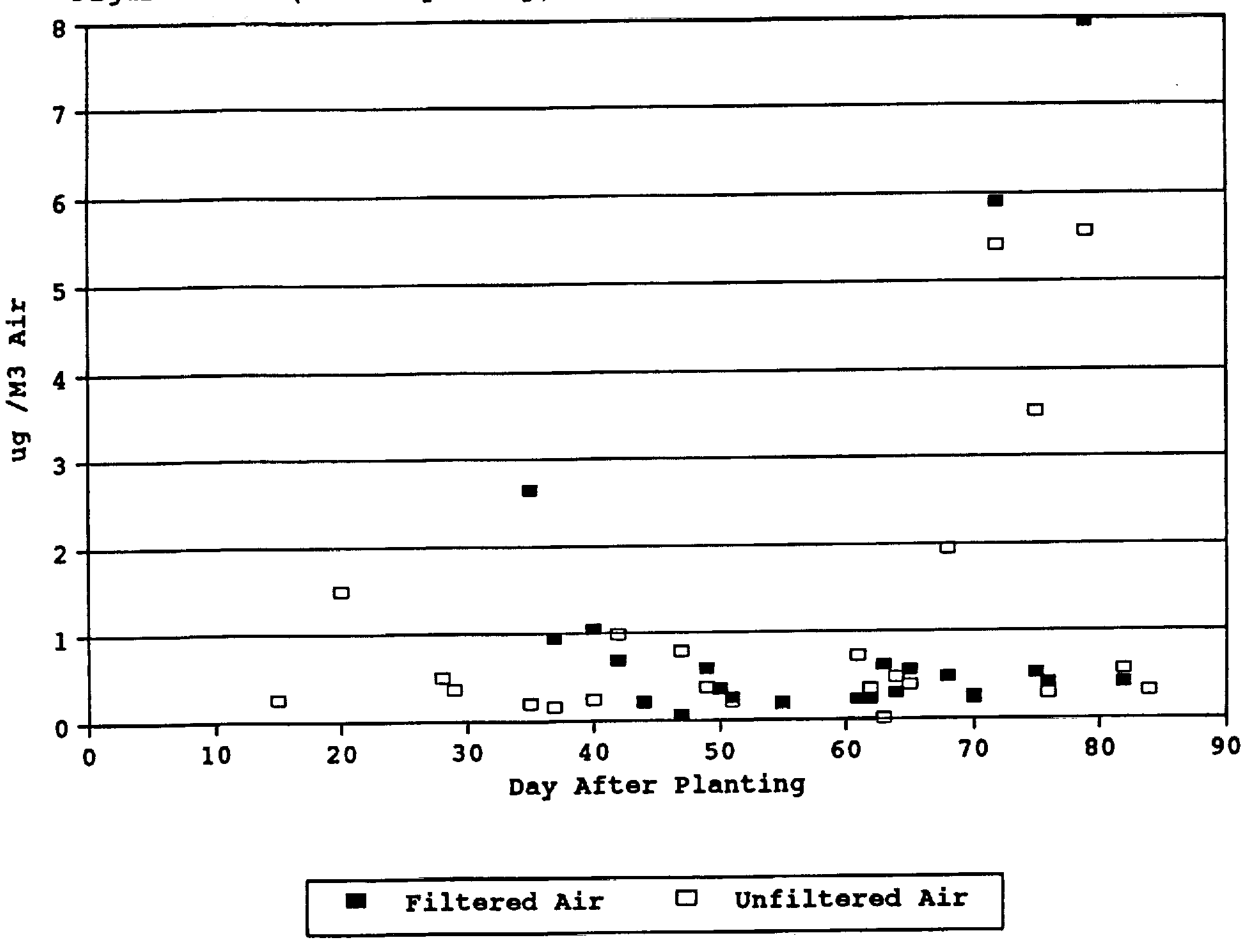


Figure 13. 2-Butoxyethanol Concentrations-Wheat Study (BWT931)

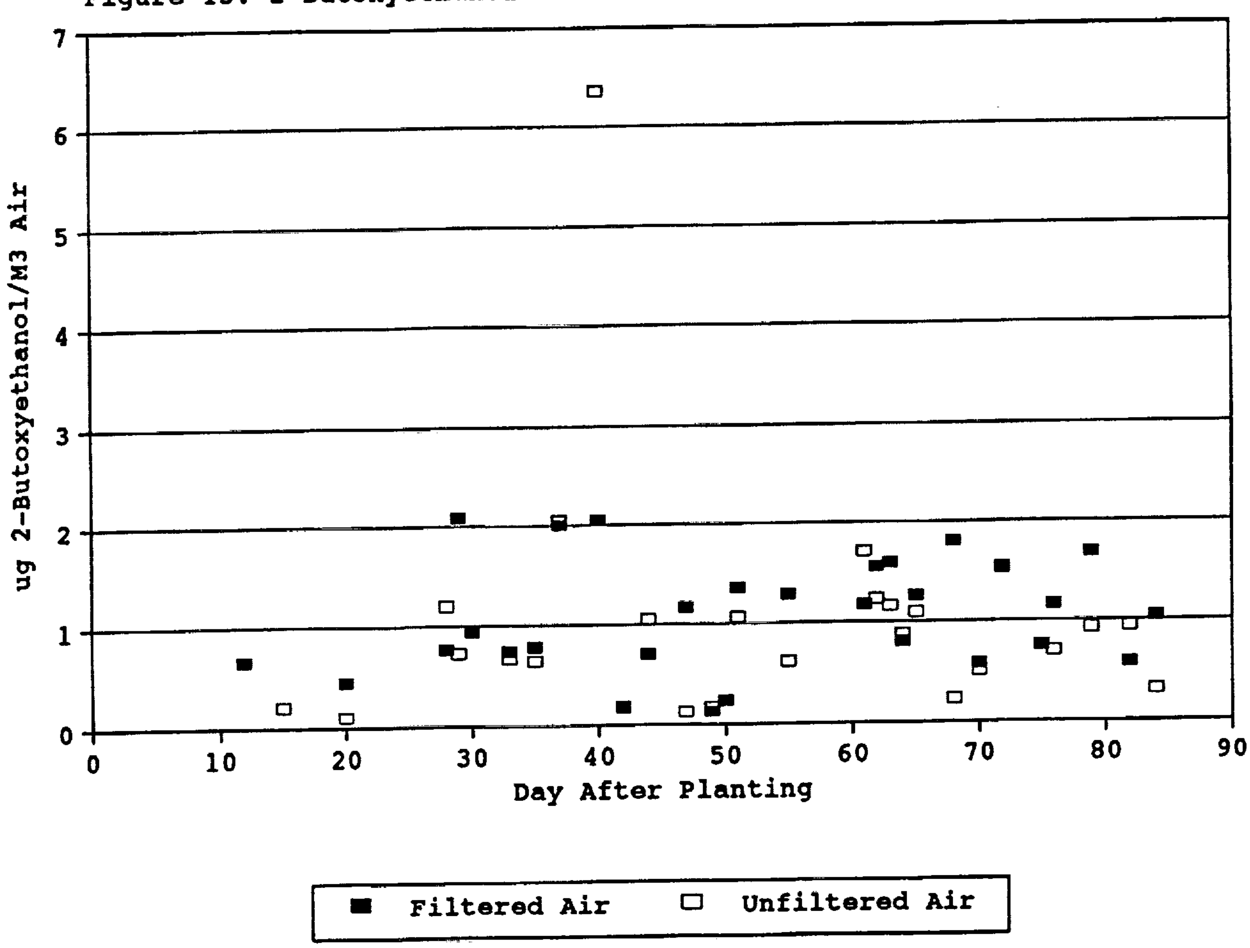


Figure 14. Tetrahydrofuran Concentrations-Wheat Study (BWT931)

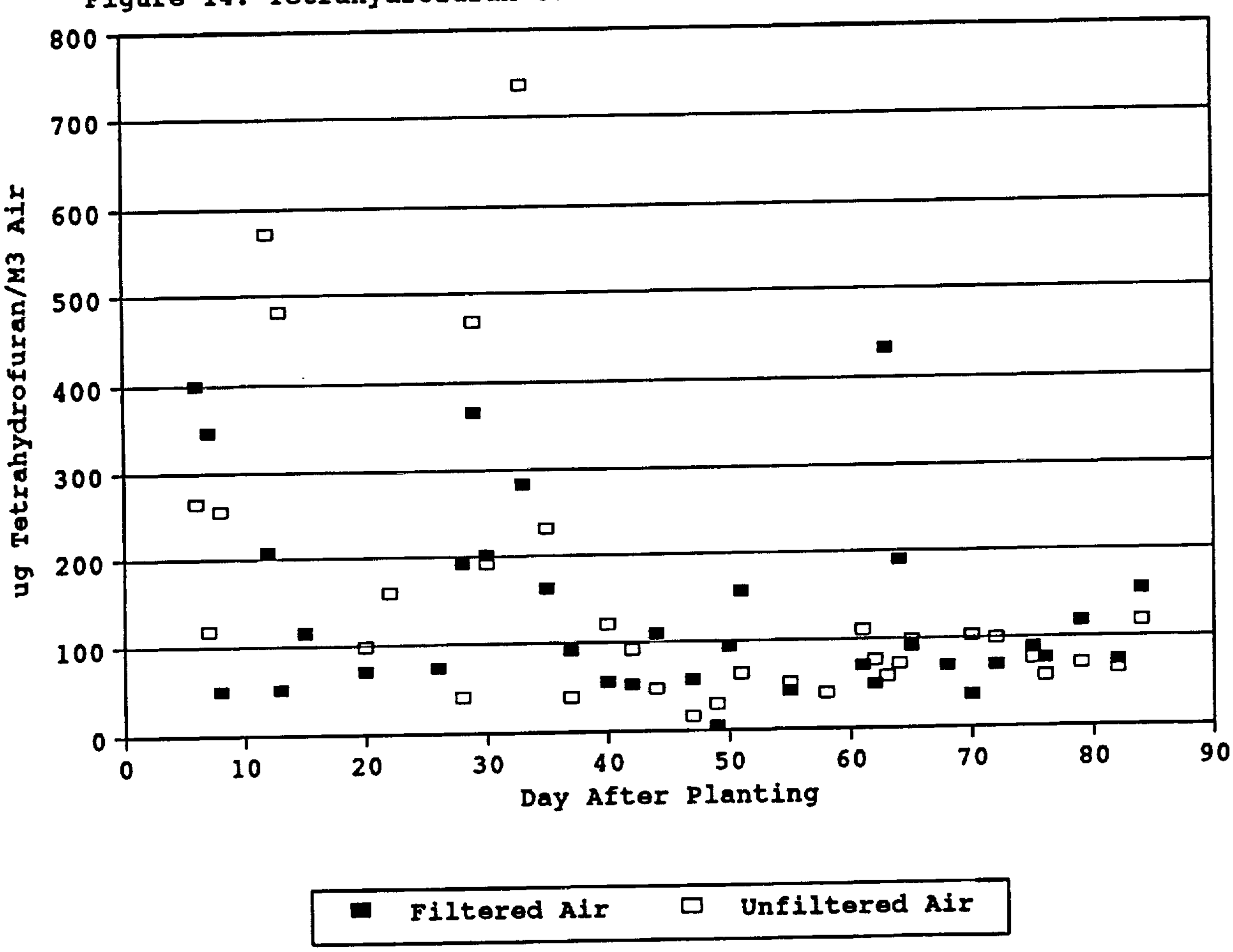


Figure 15. Toluene Concentrations-Wheat Study (BWT931)

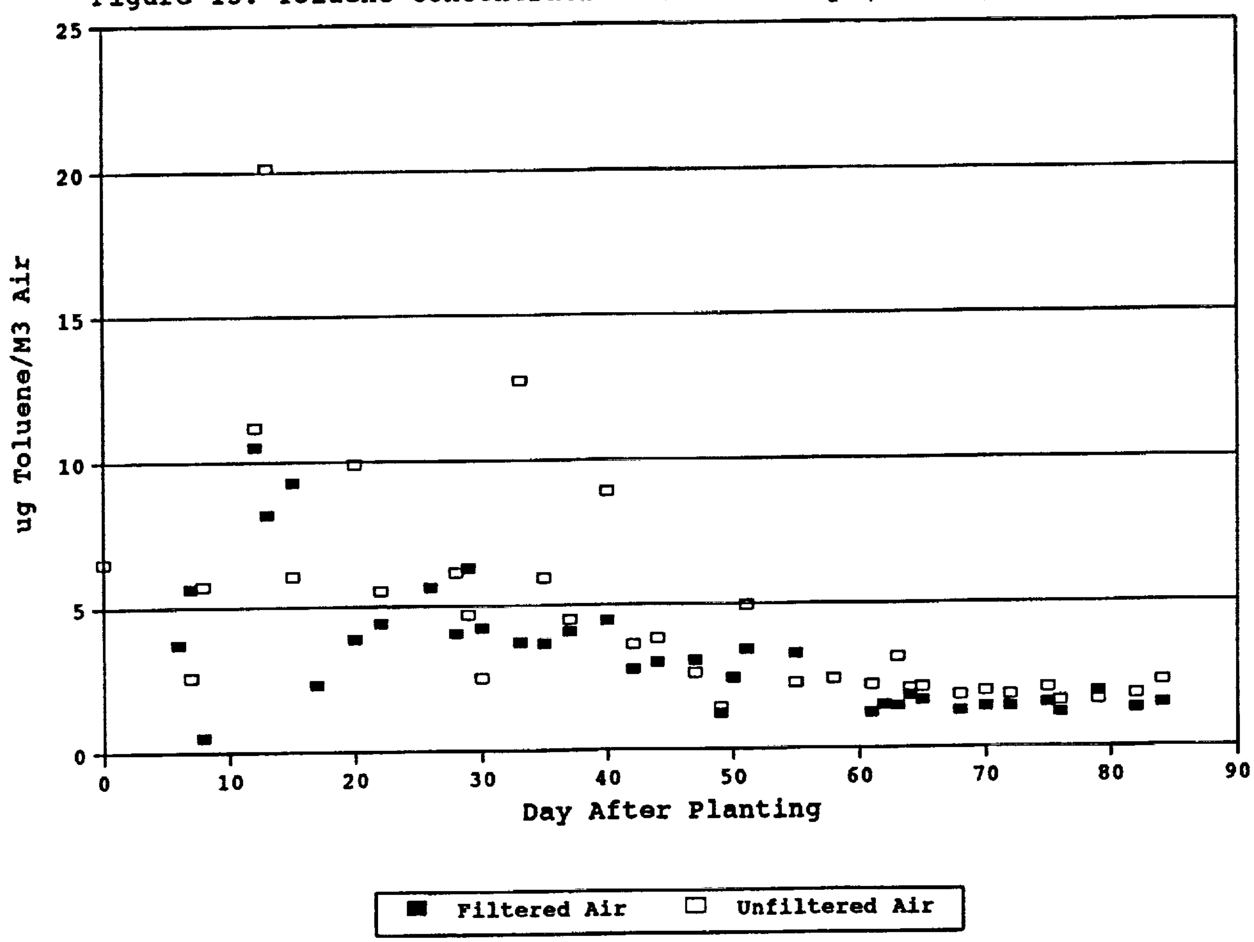


Figure 16. Trimethylsilanol Concentrations-Wheat Study (BWT931)

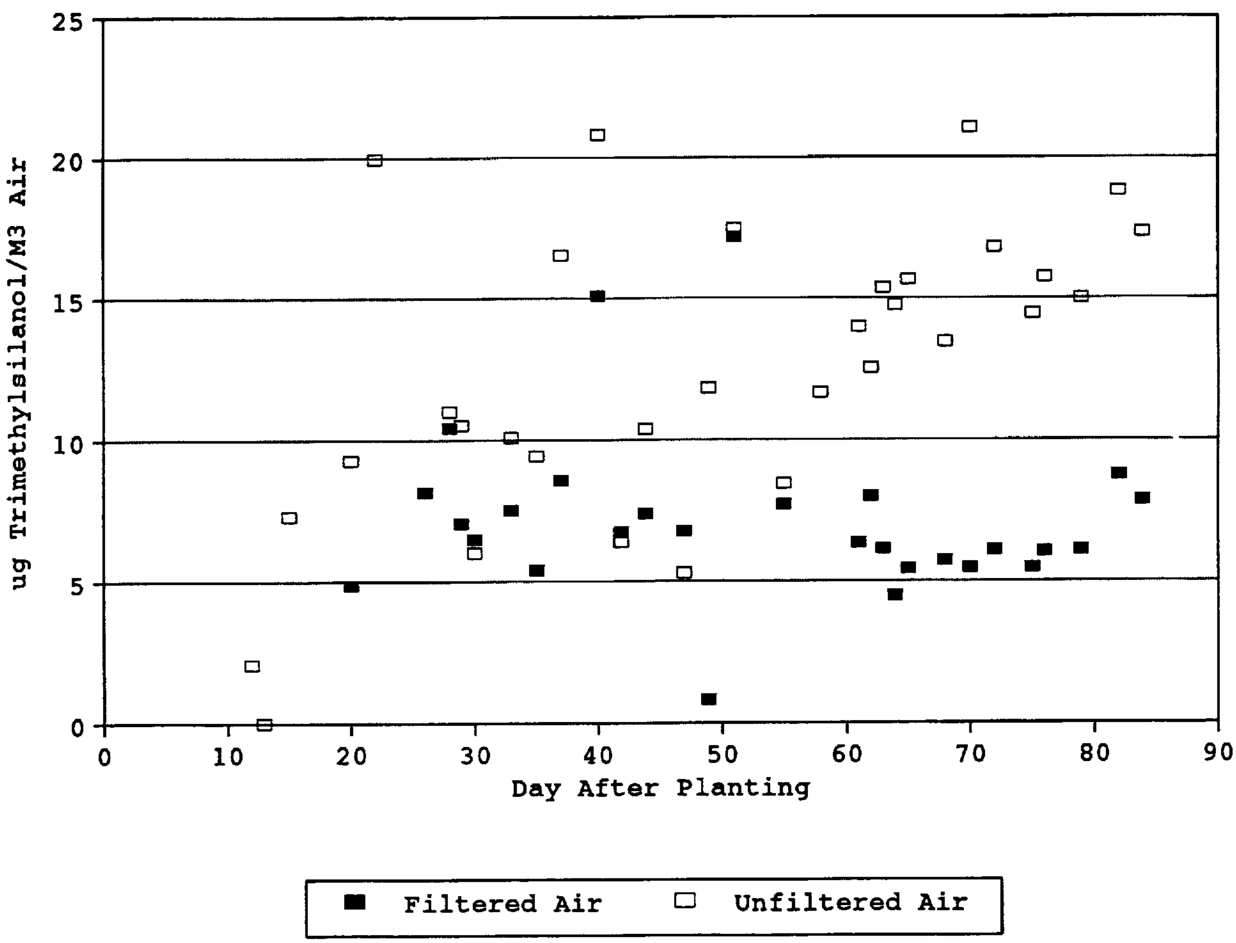


Figure 17. Hexamethylcyclotrisiloxane Concentrations-Wheat Study(BWT931)

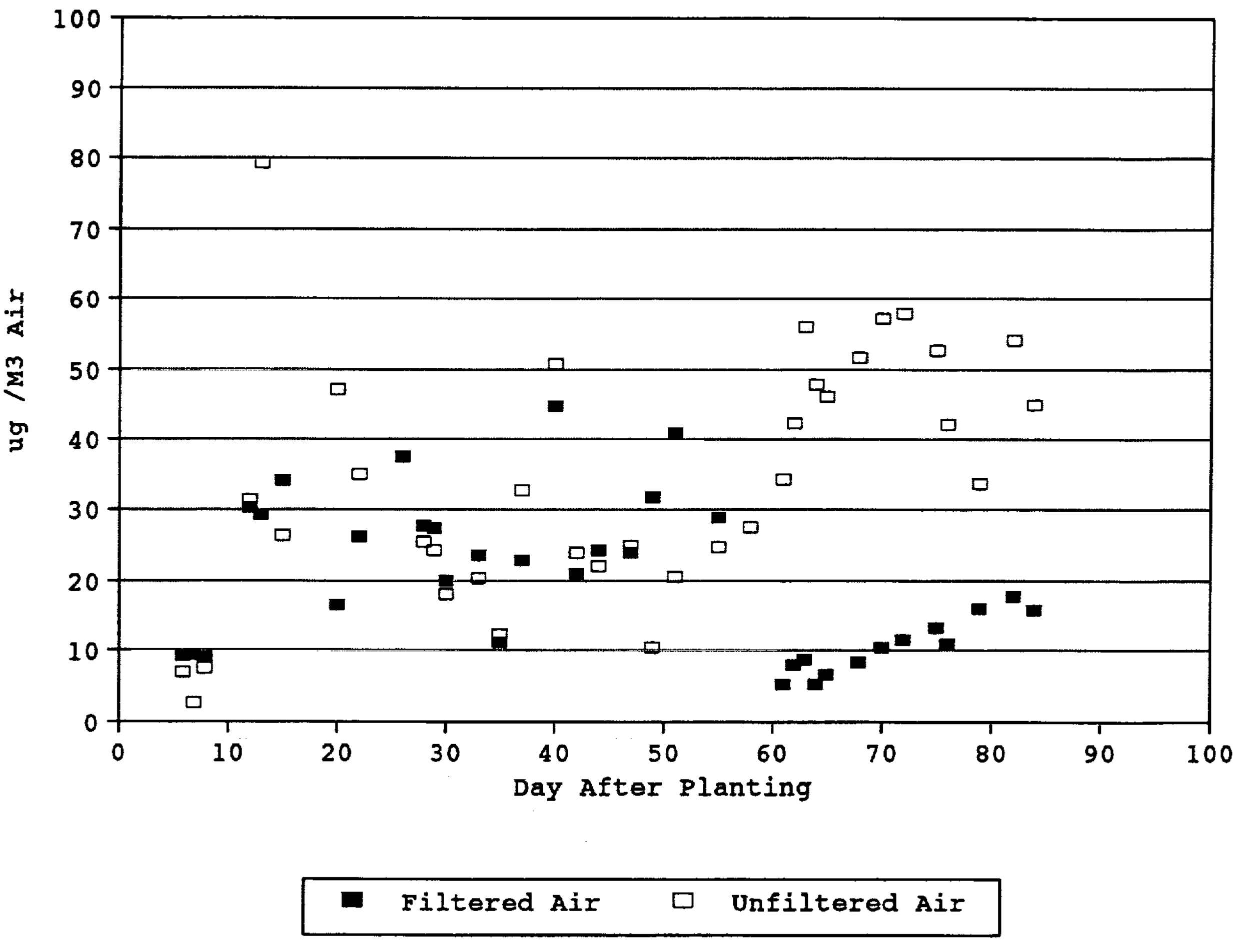


Figure 18. Octamethylcyclotetrasiloxane Concentrations-Wheat Study(BWT931)

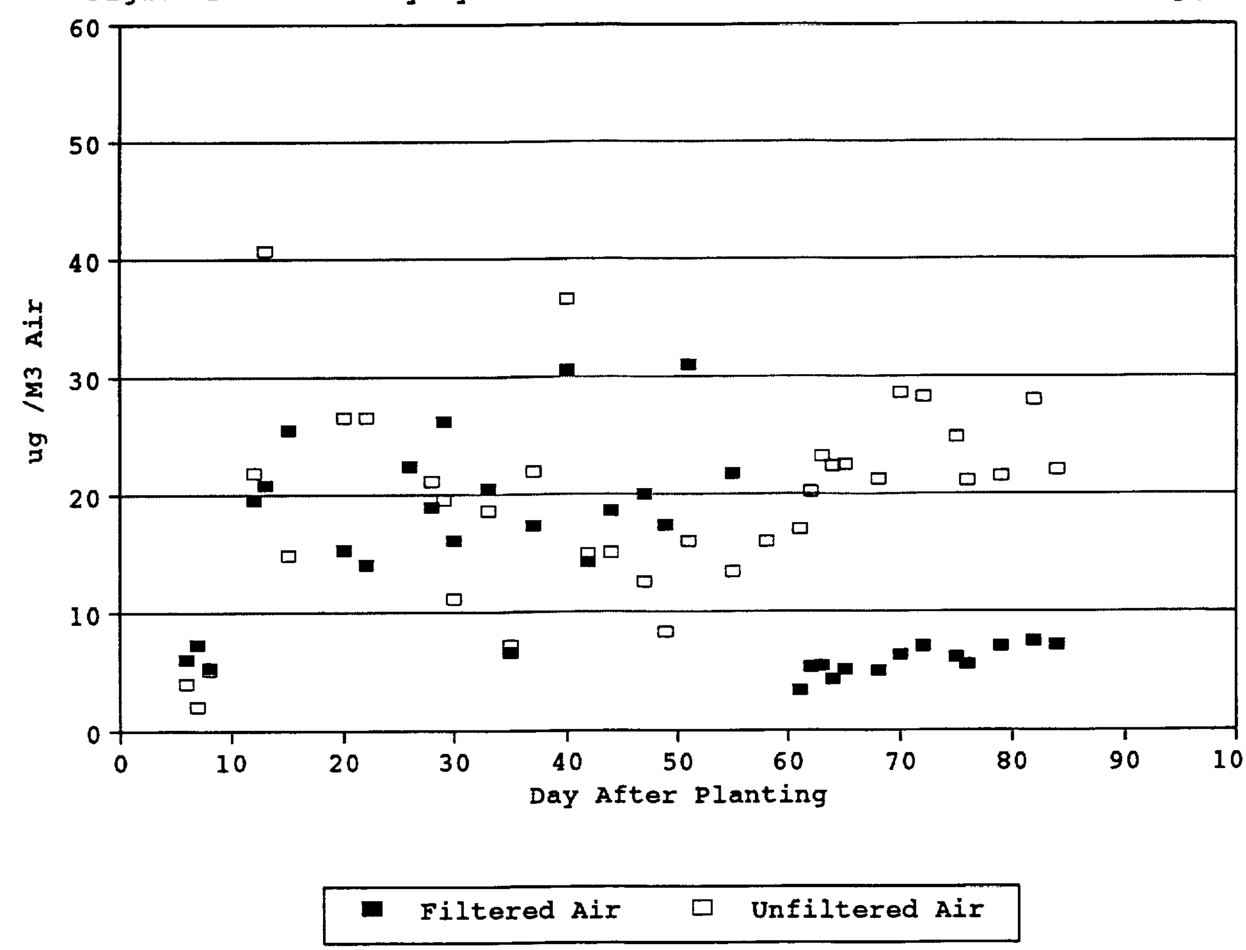


Figure 19. Decamethylcyclopentasiloxane Concentrations-Wheat Study (BWT931)

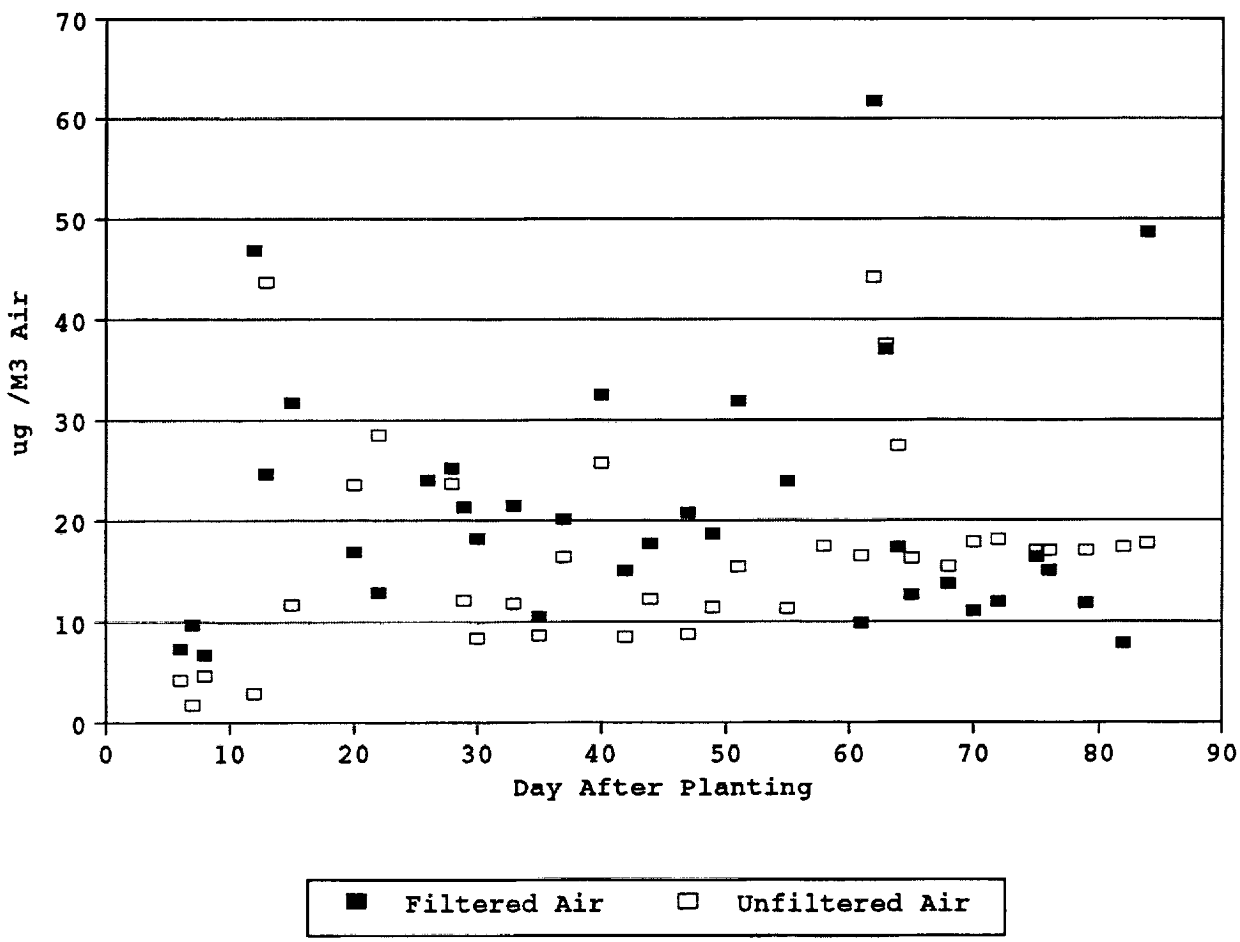


Figure 20. Dodecamethylcyclohexasiloxane Concentrations-Wheat Study(BWT931)

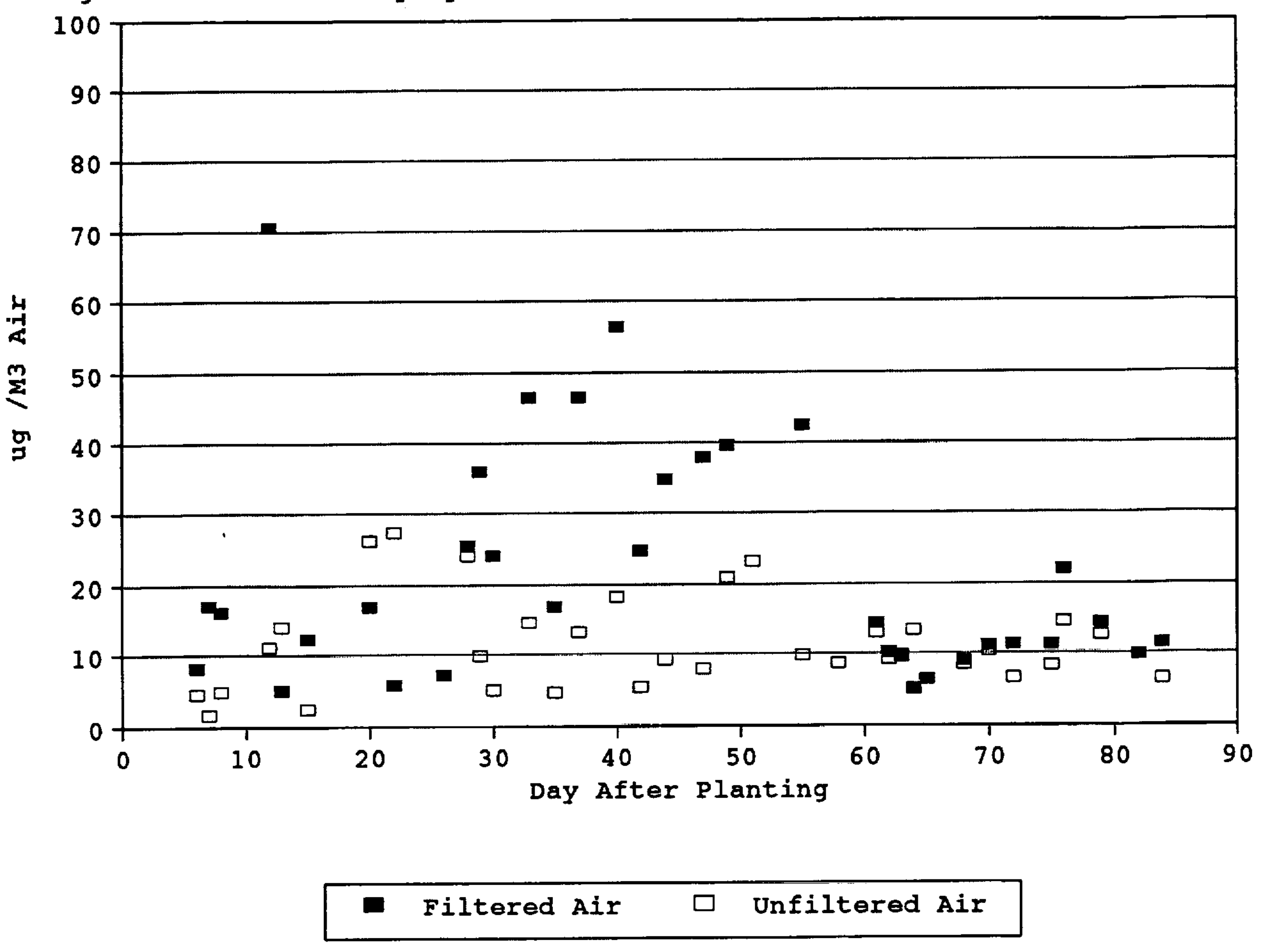


Figure 21. 2,6-Ditbutyl-2,5-cyclohexadiene-1,4-dione Concentrations-Wheat Study

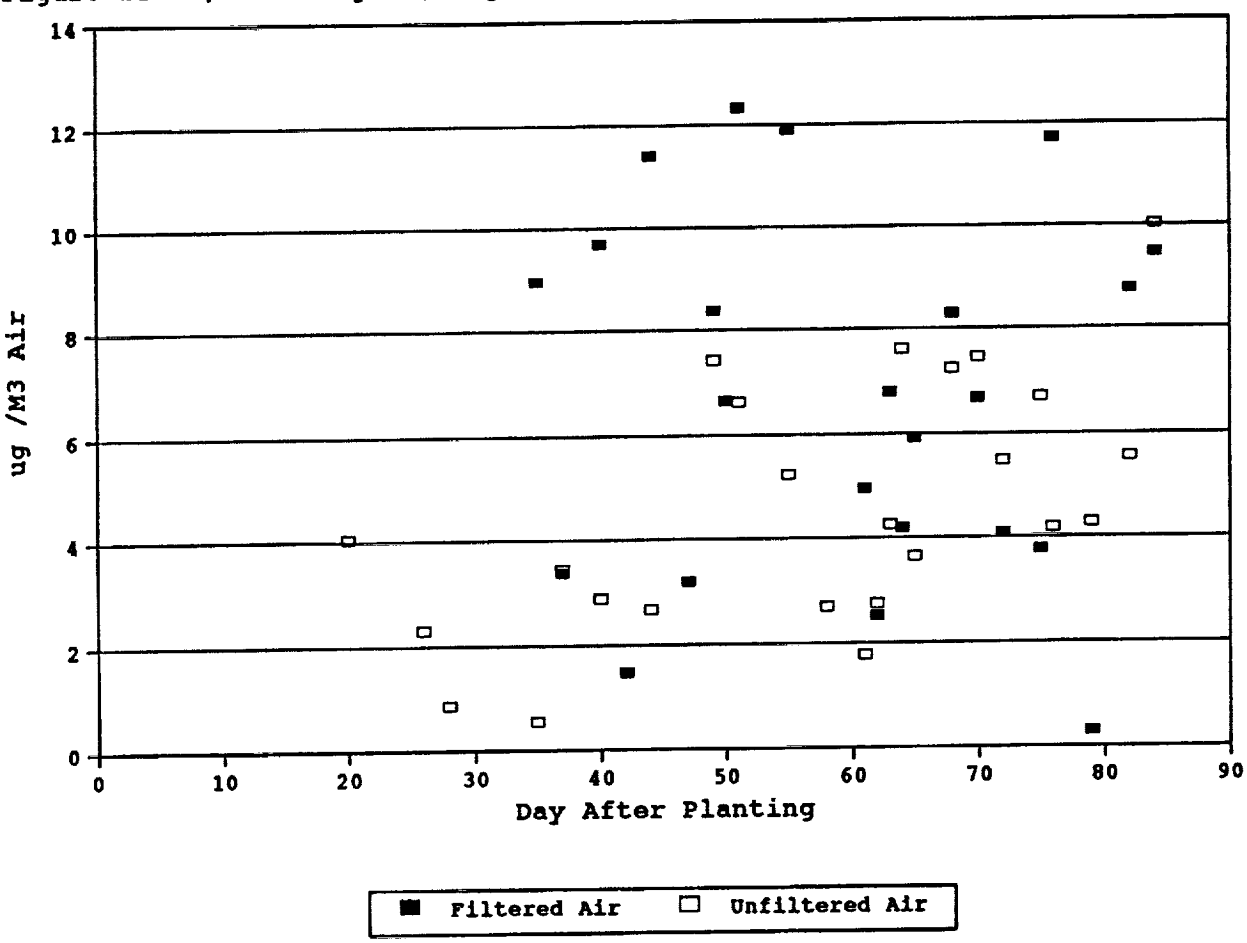


Figure 22. 2,6-Di-tert-butyl-p-cresol Concentrations-Wheat Study(BWT931)

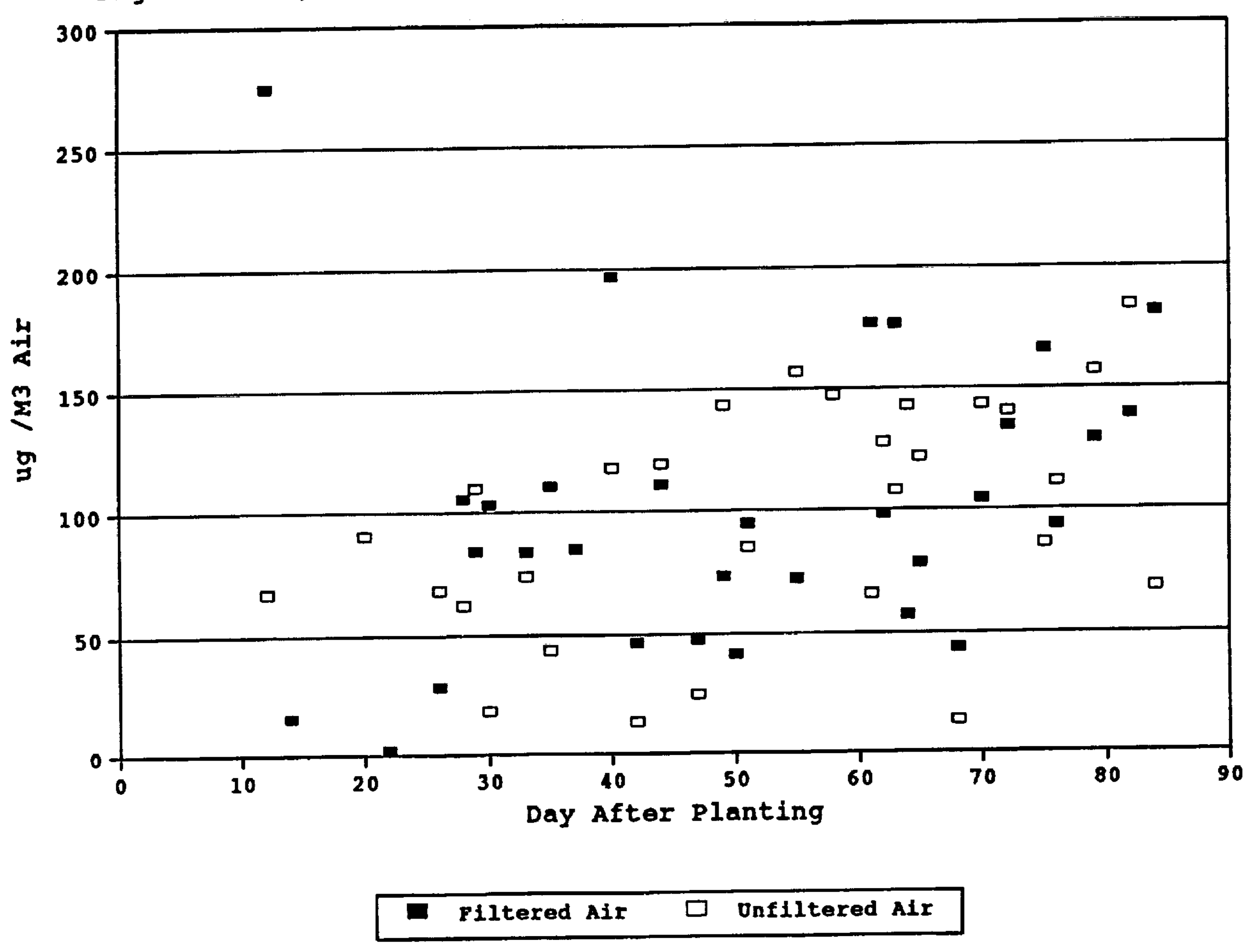


Figure 23. 2 and 3-Methylfuran Concentrations-Wheat Study(BWT931)

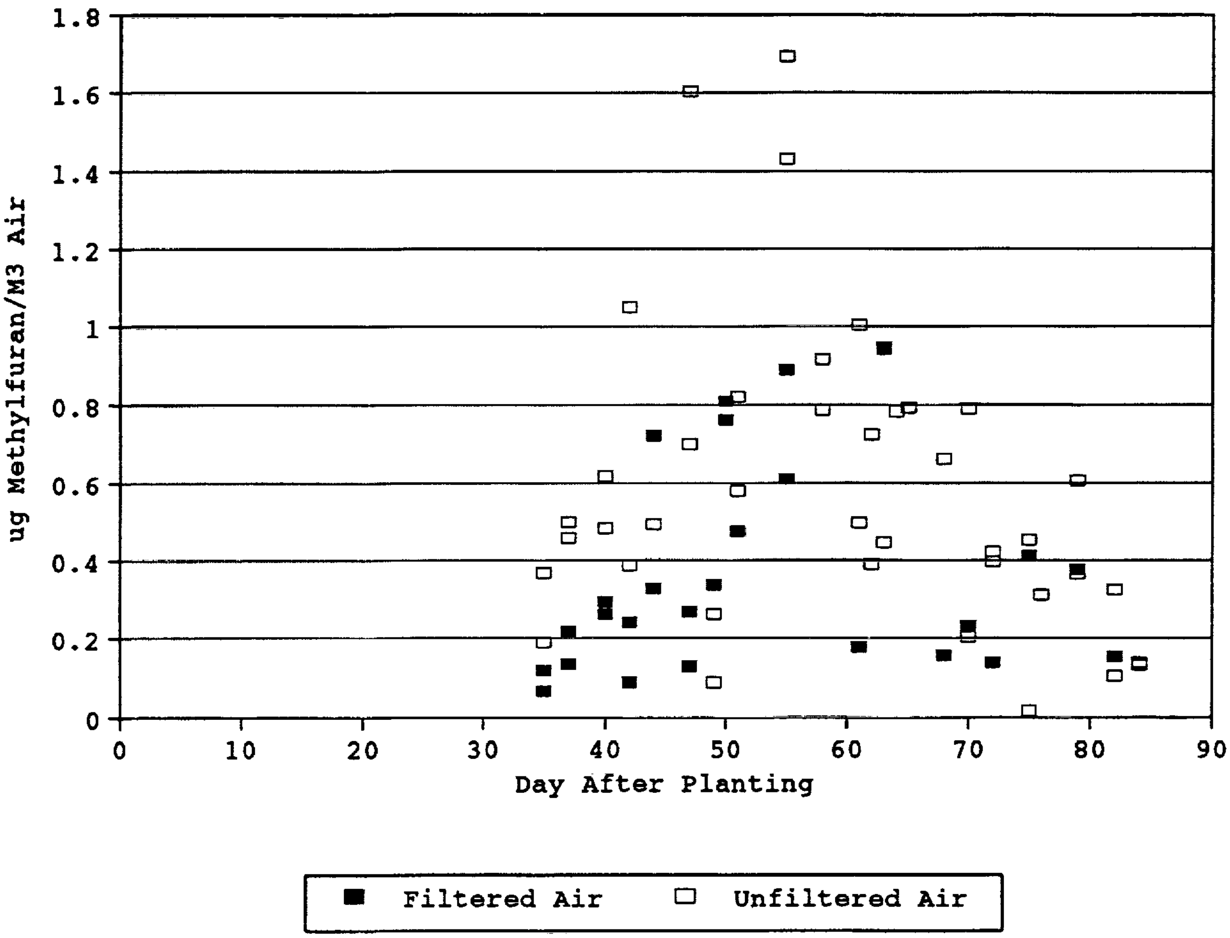


Figure 24. 2-Methylbutane Concentrations-Wheat Study (BWT931)

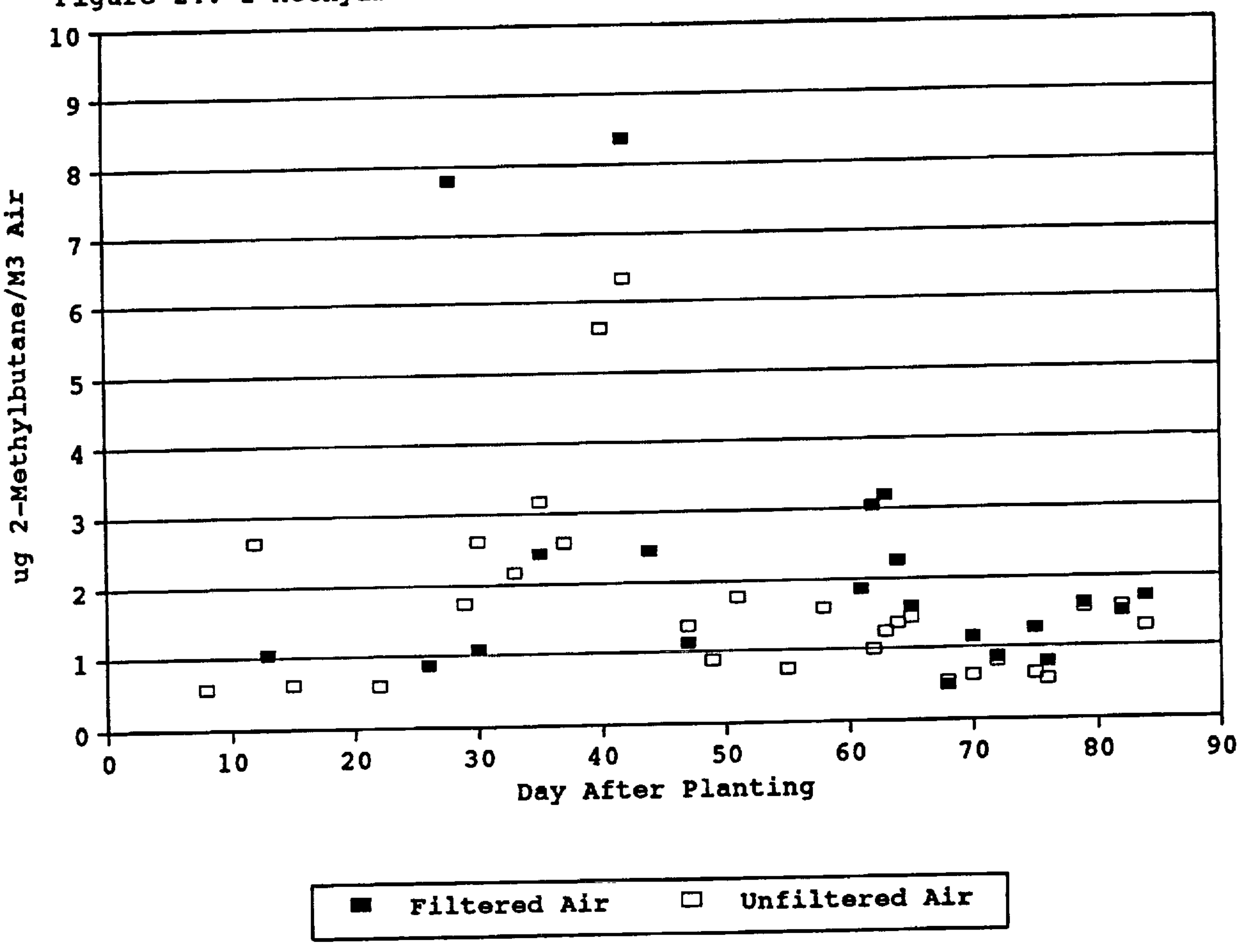


Figure 25. 1-Butanol Concentrations- Wheat Study (BWT931)

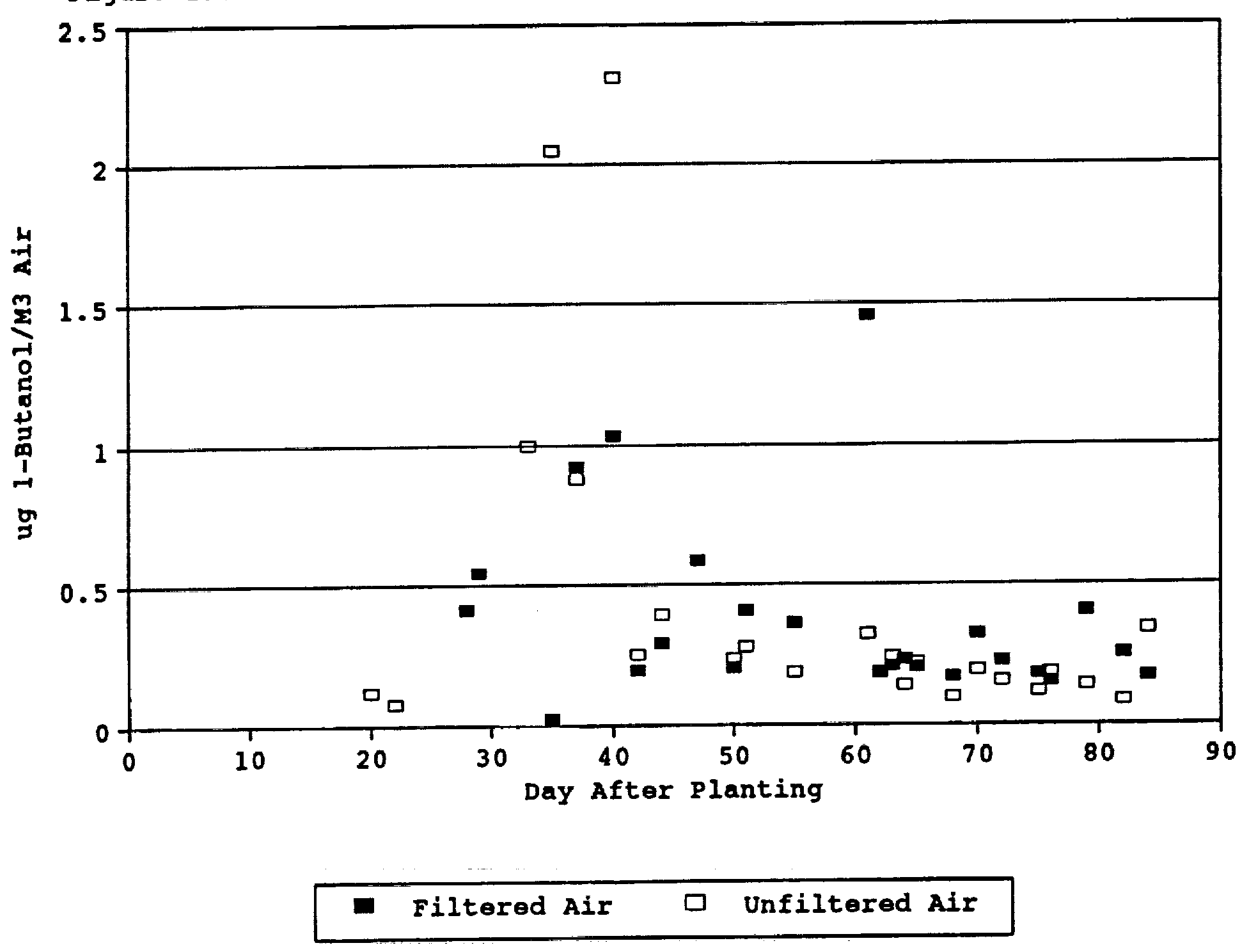


Figure 26. 2-Ethyl-1-hexanol Concentrations-Wheat Study (BWT931)

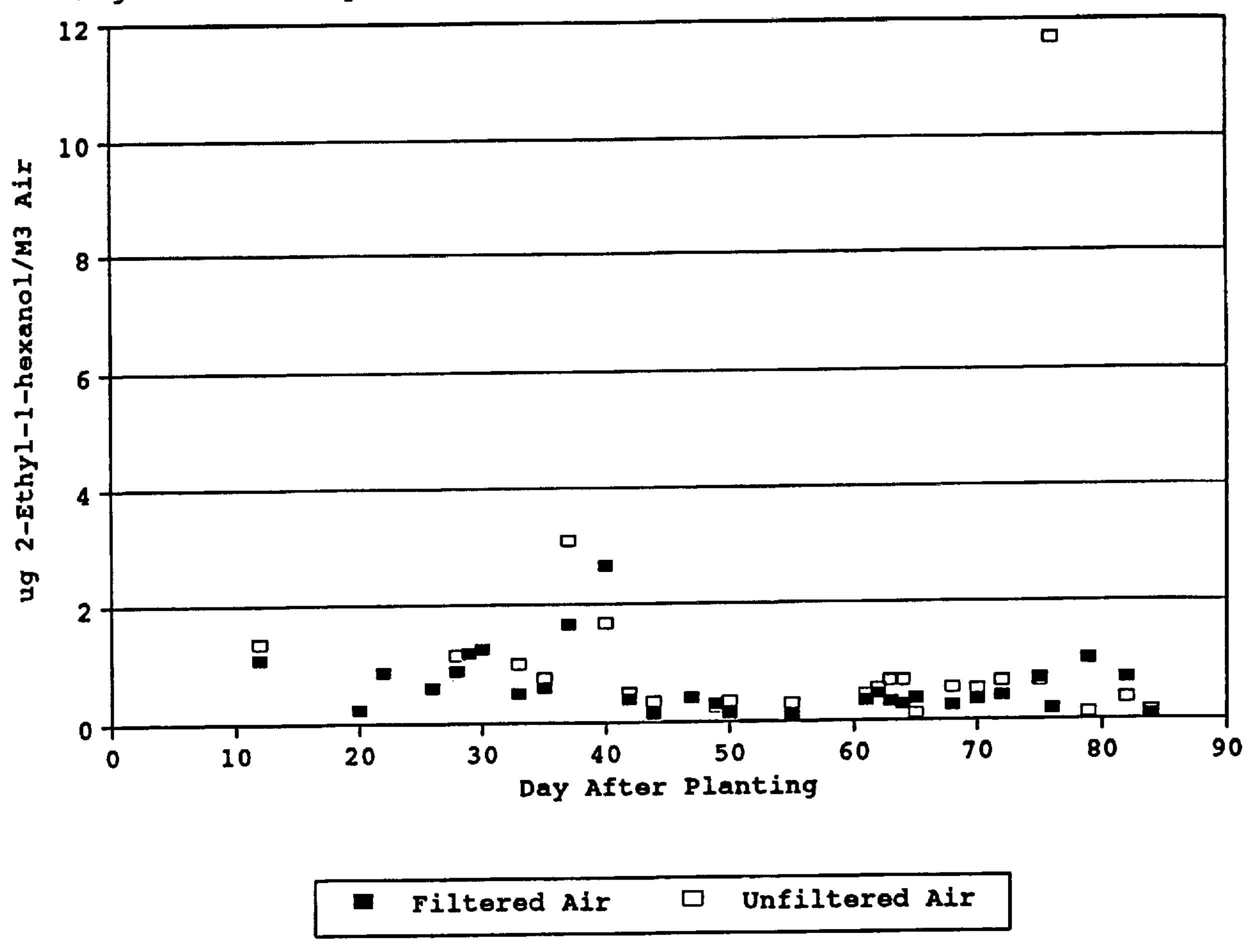


Figure 27. Hexanal Concentrations-Wheat Study (BWT931)

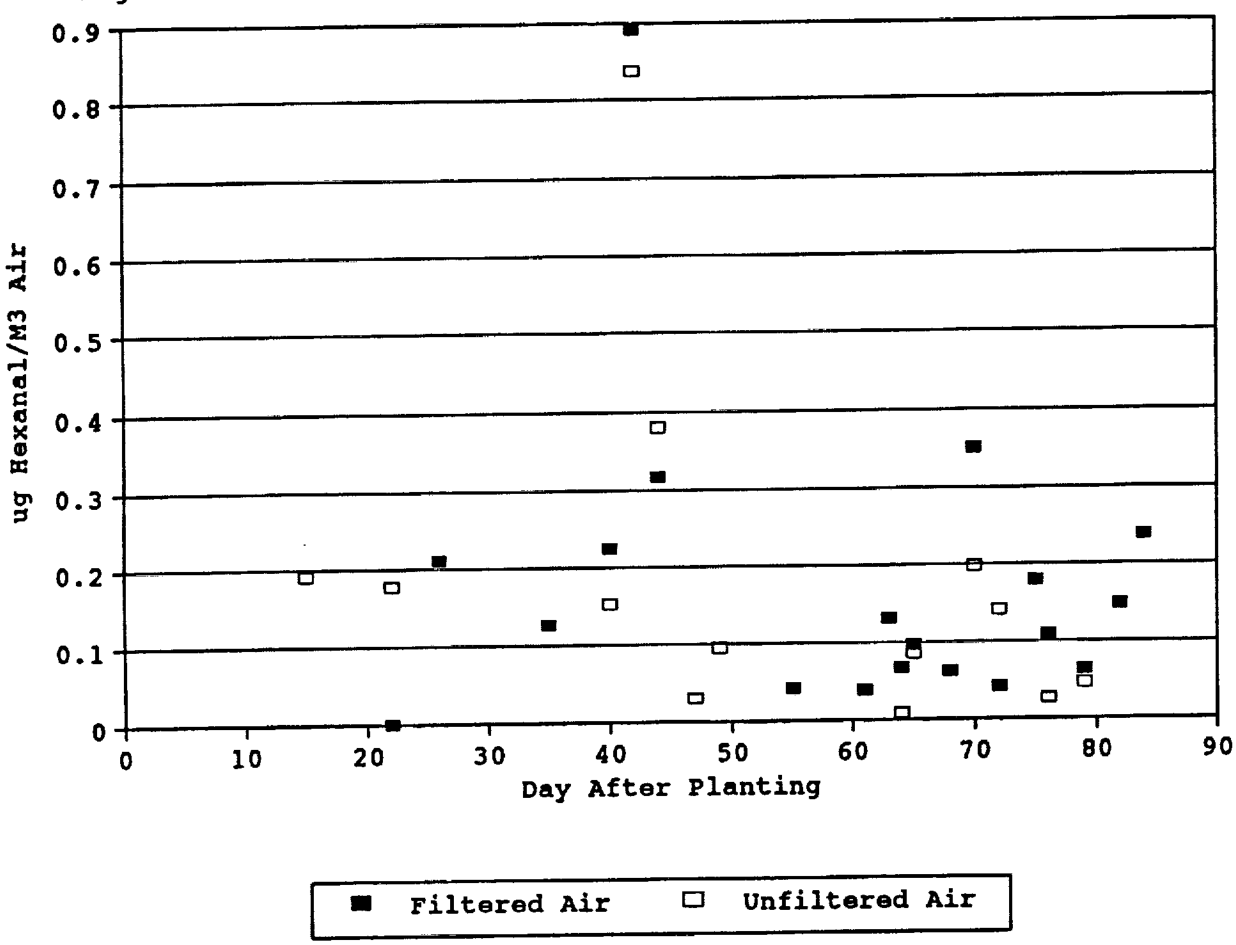


Figure 28. Heptanal Concentrations-Wheat Study (BWT931)

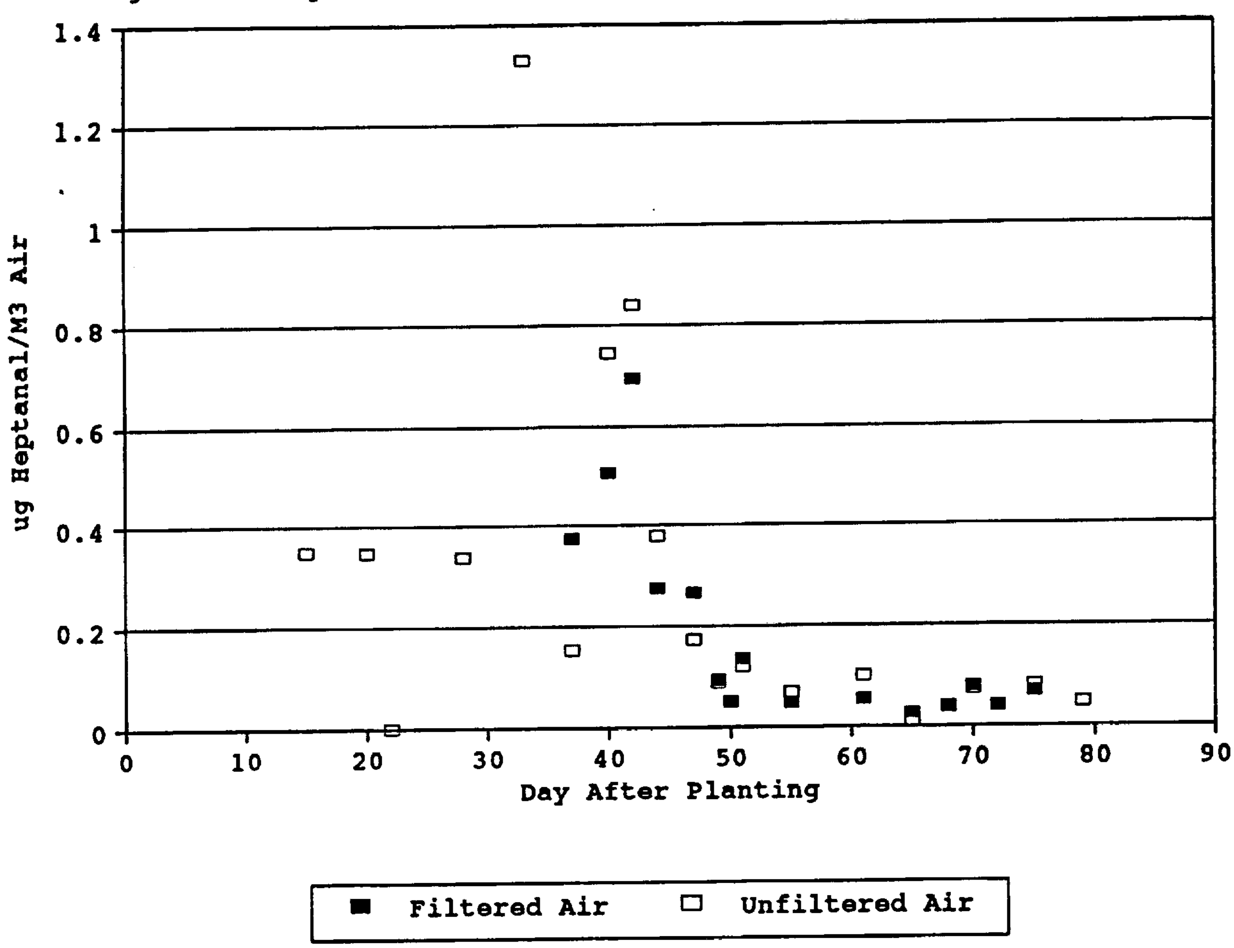


Figure 29. Nonanal Concentrations-Wheat Study (BWT931)

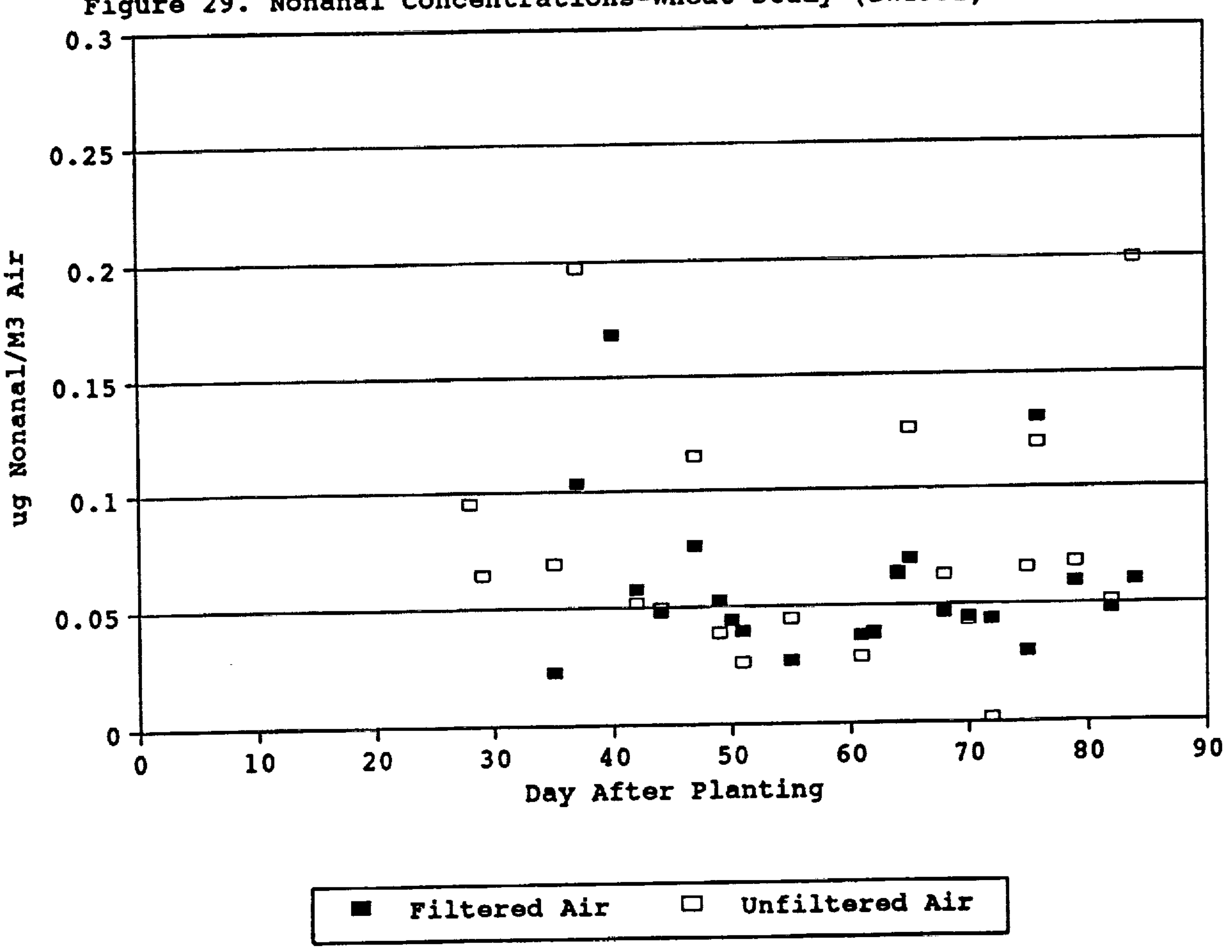


Figure 30. Dimethylaminoacetonitrile Concentrations-Wheat Study(BWT931)

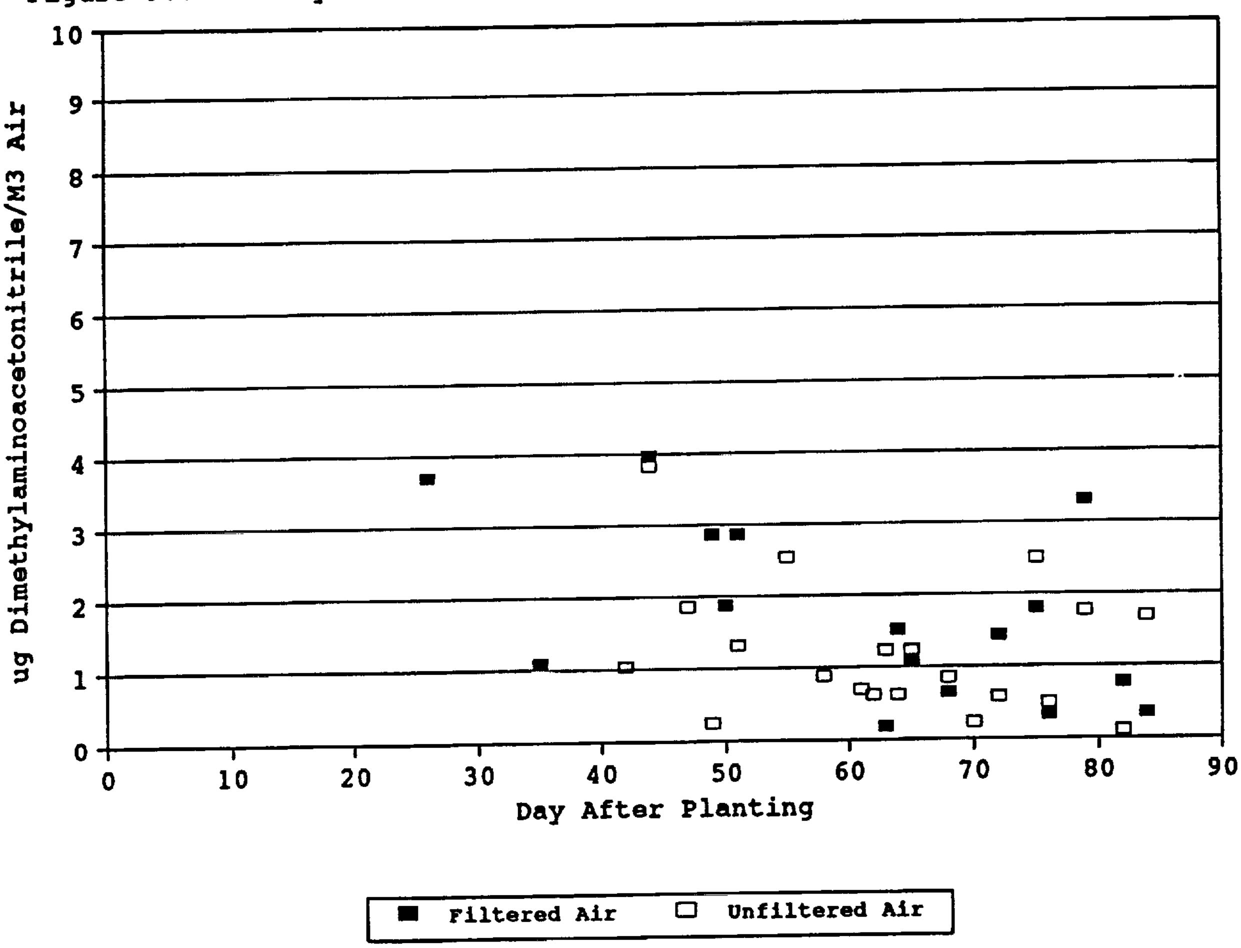


Figure 31. Tetramethylthiourea Concentrations-Wheat Study (BWT931)

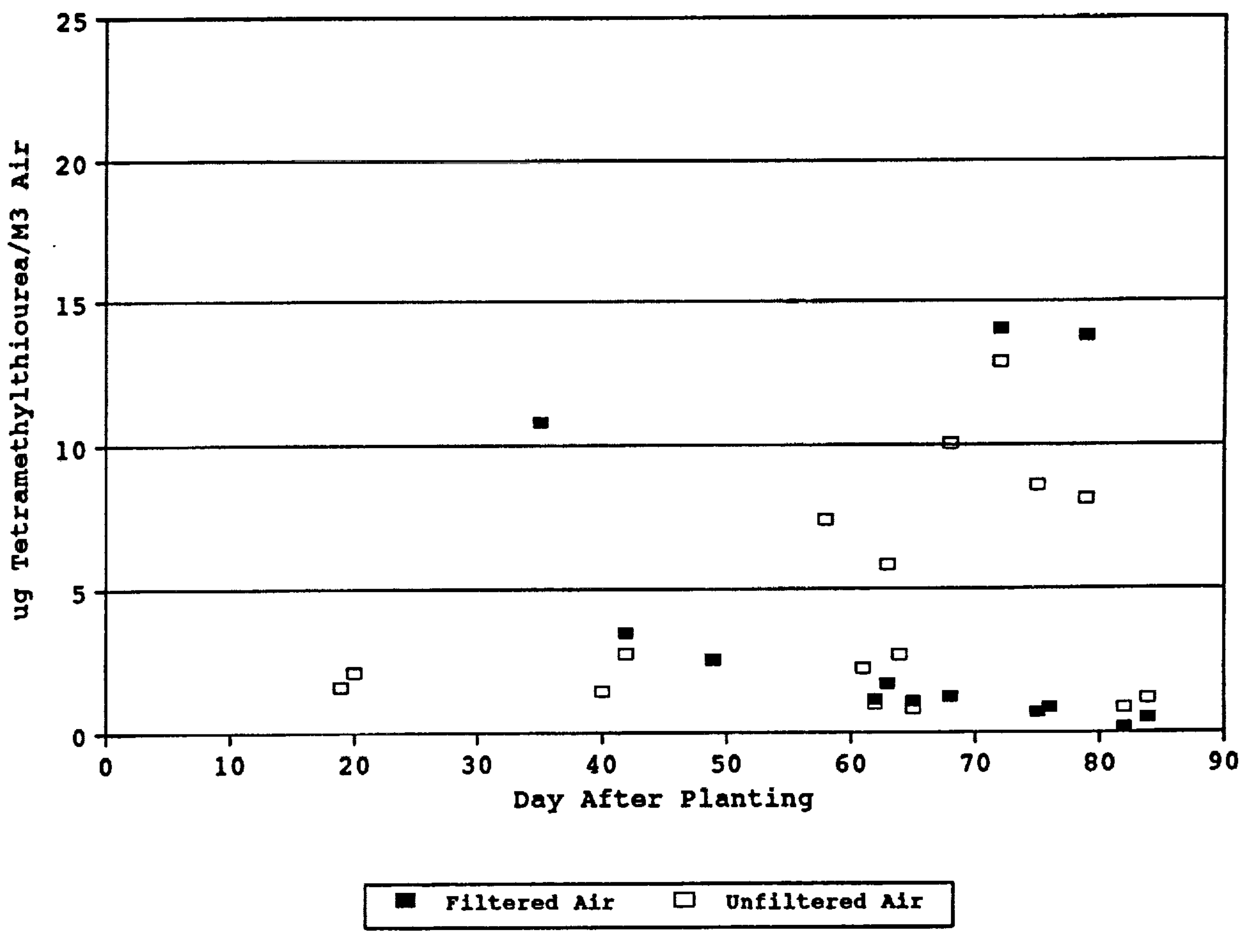


Figure 32. Tetramethylurea Concentrations-Wheat Study (BWT931)

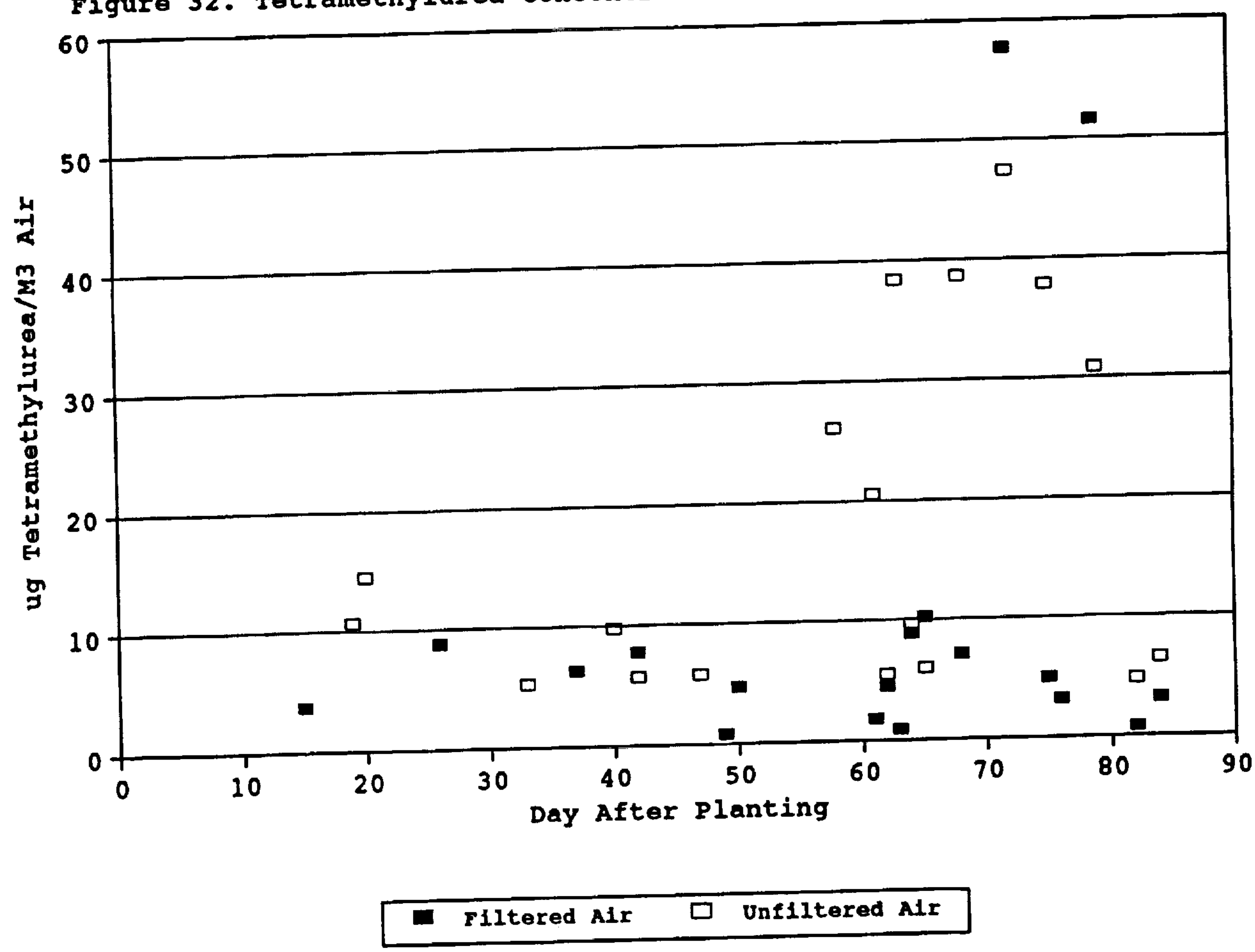


Figure 33. Benzothiazole Concentrations-Wheat Study (BWT931)

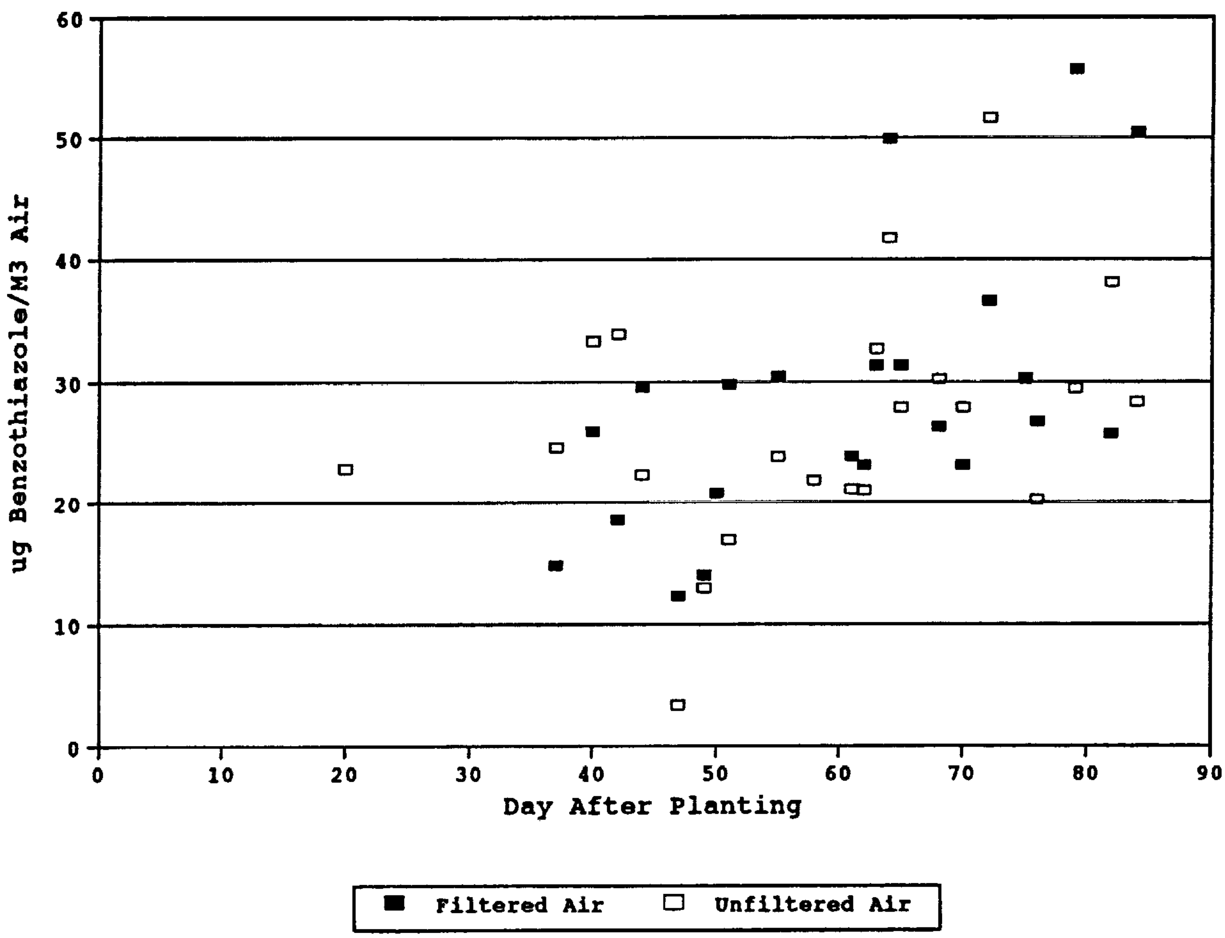


Figure 34. Benzaldehyde Concentrations-Wheat Study (BWT931)

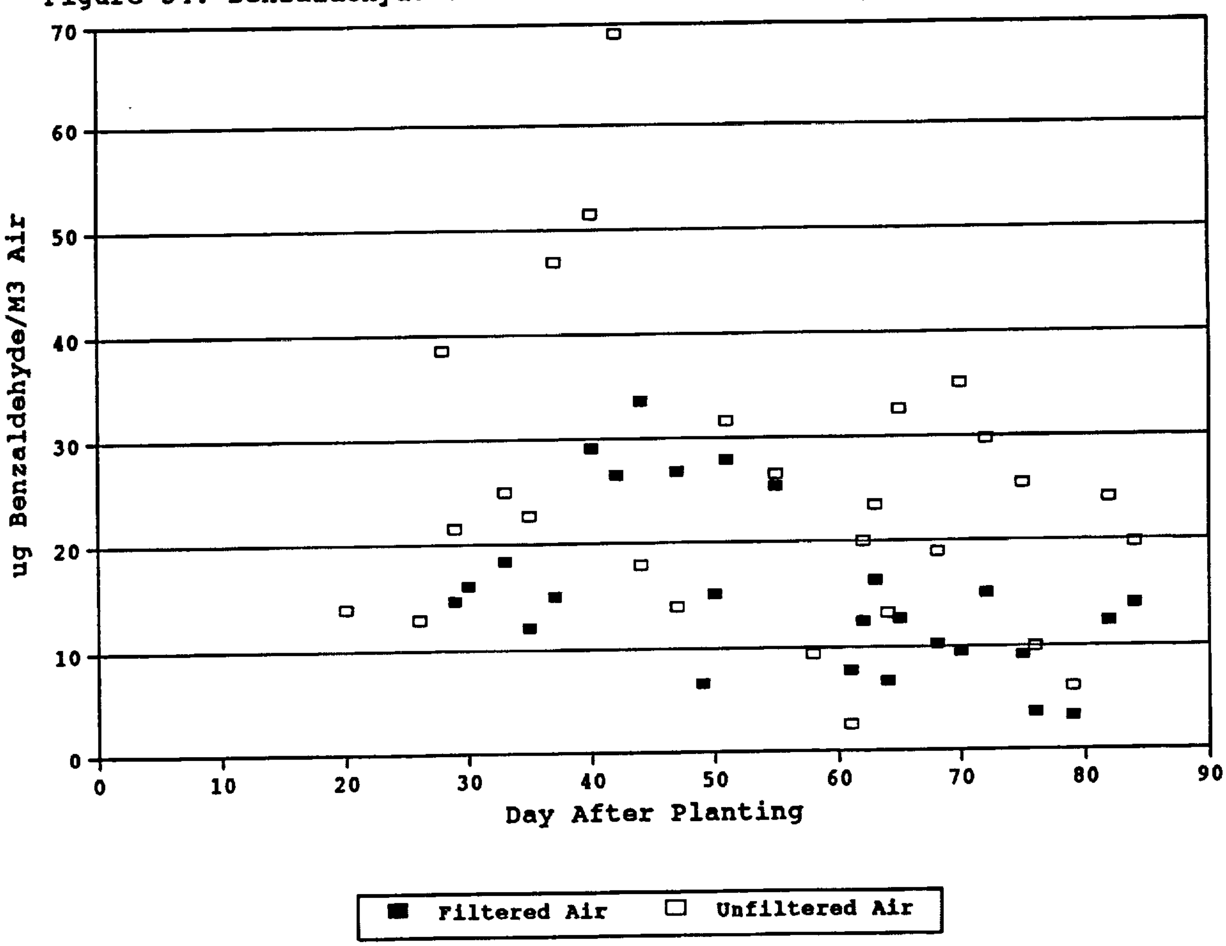


Figure 35. Phenol Concentrations- Wheat Study (BWT931)

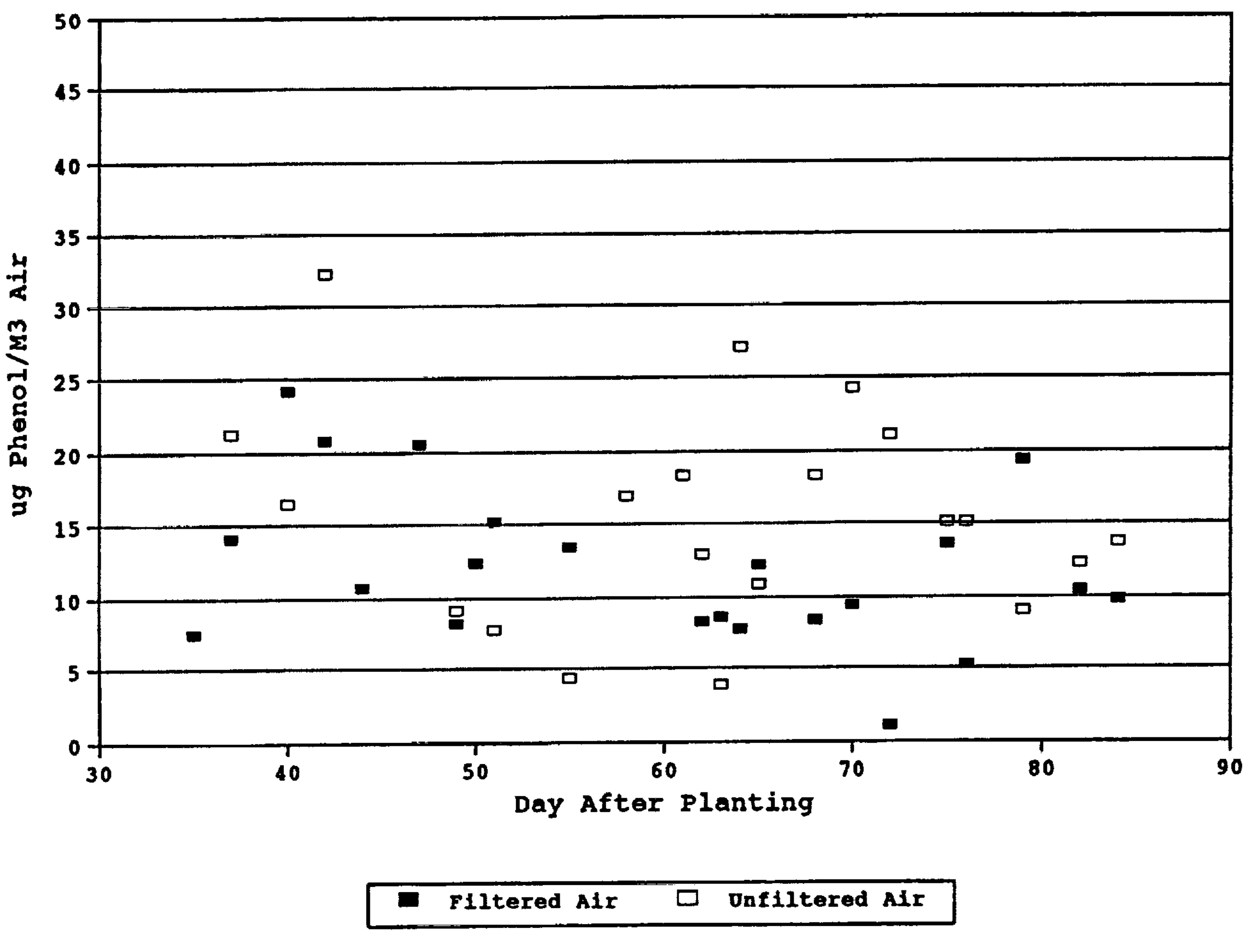


Figure 36. 2-Methylpropene Concentrations-Wheat Study (BWT931)

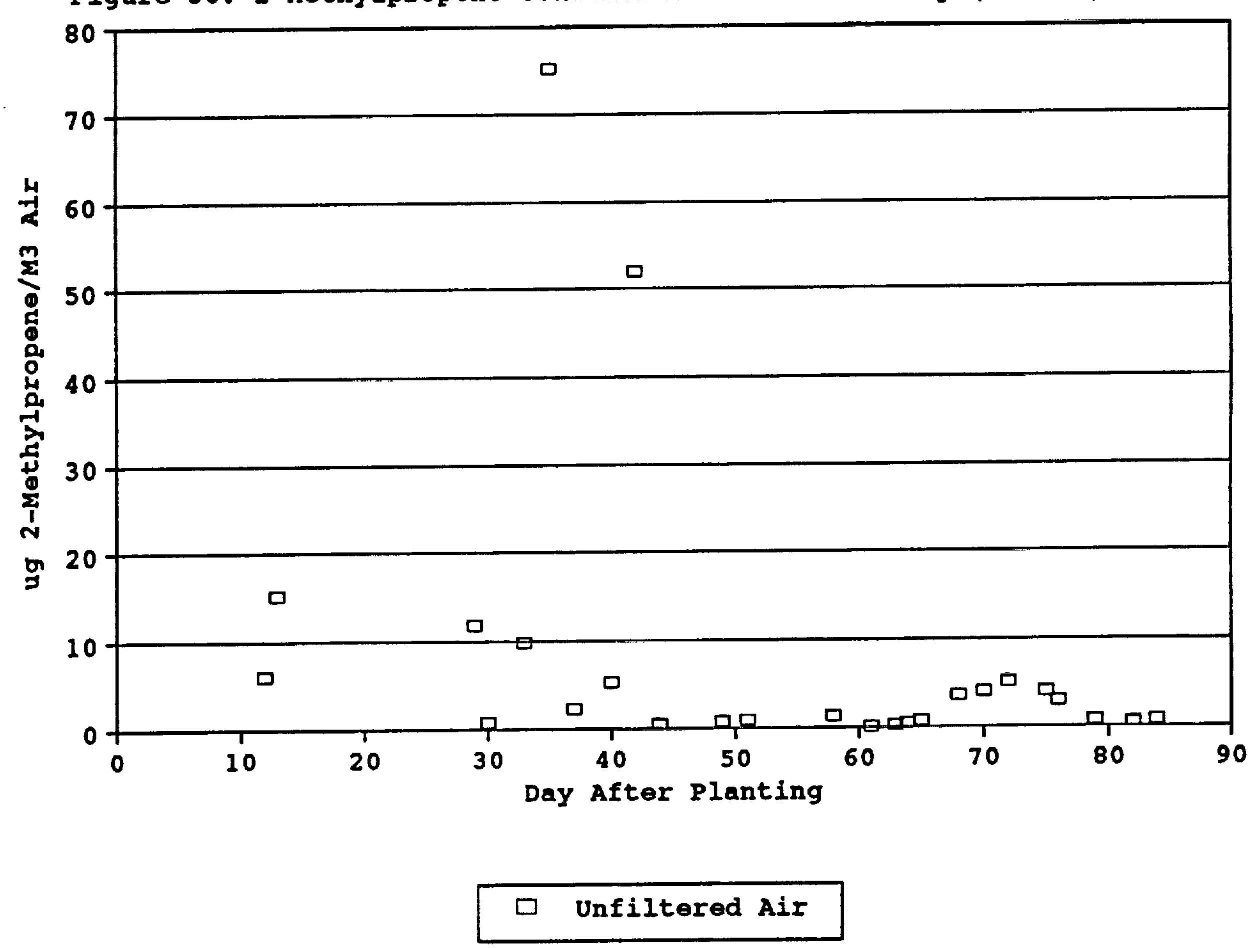


Figure 37. 3-Cyclohexene-1-carbonitrile Concentrations-Wheat Study(BWT931)

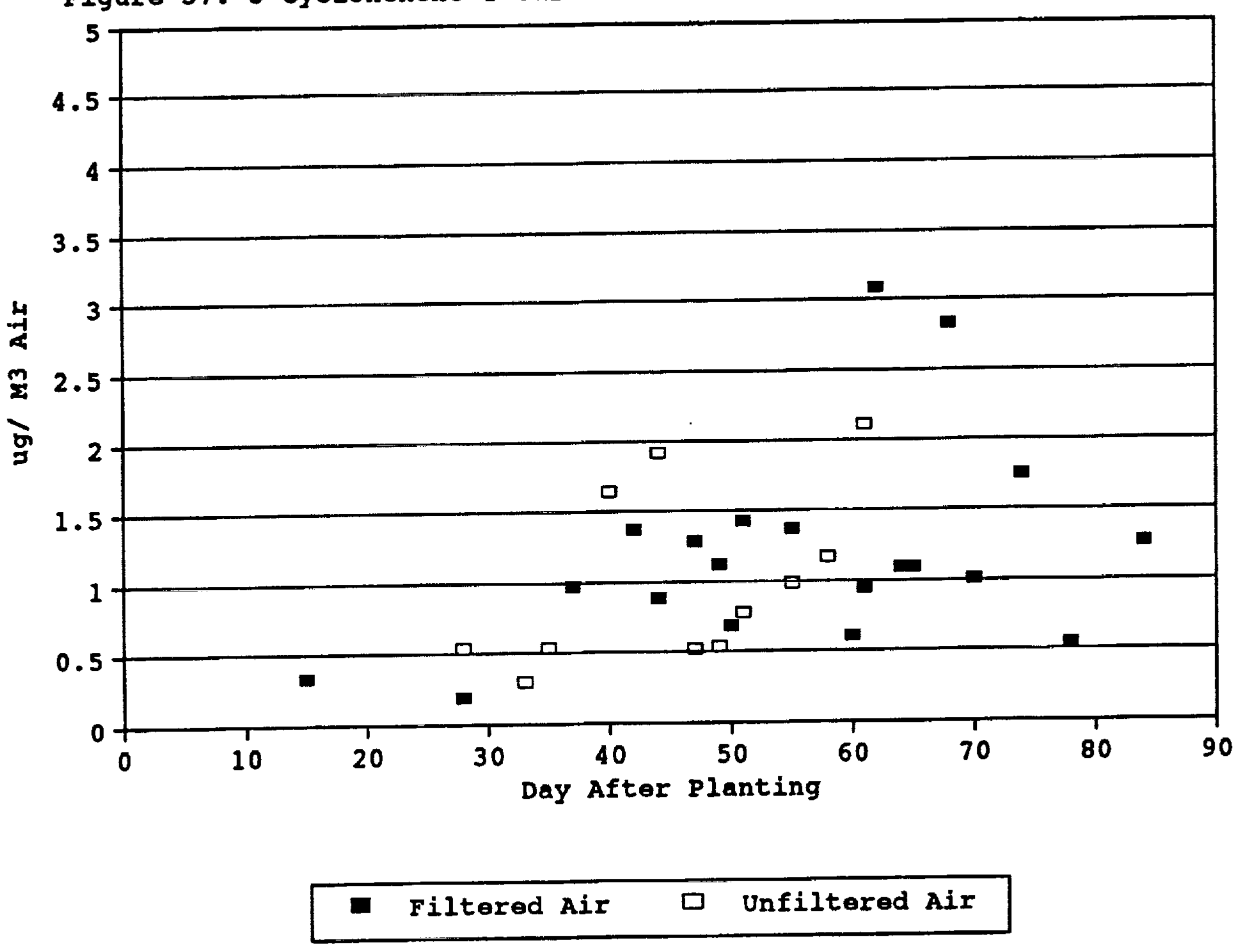
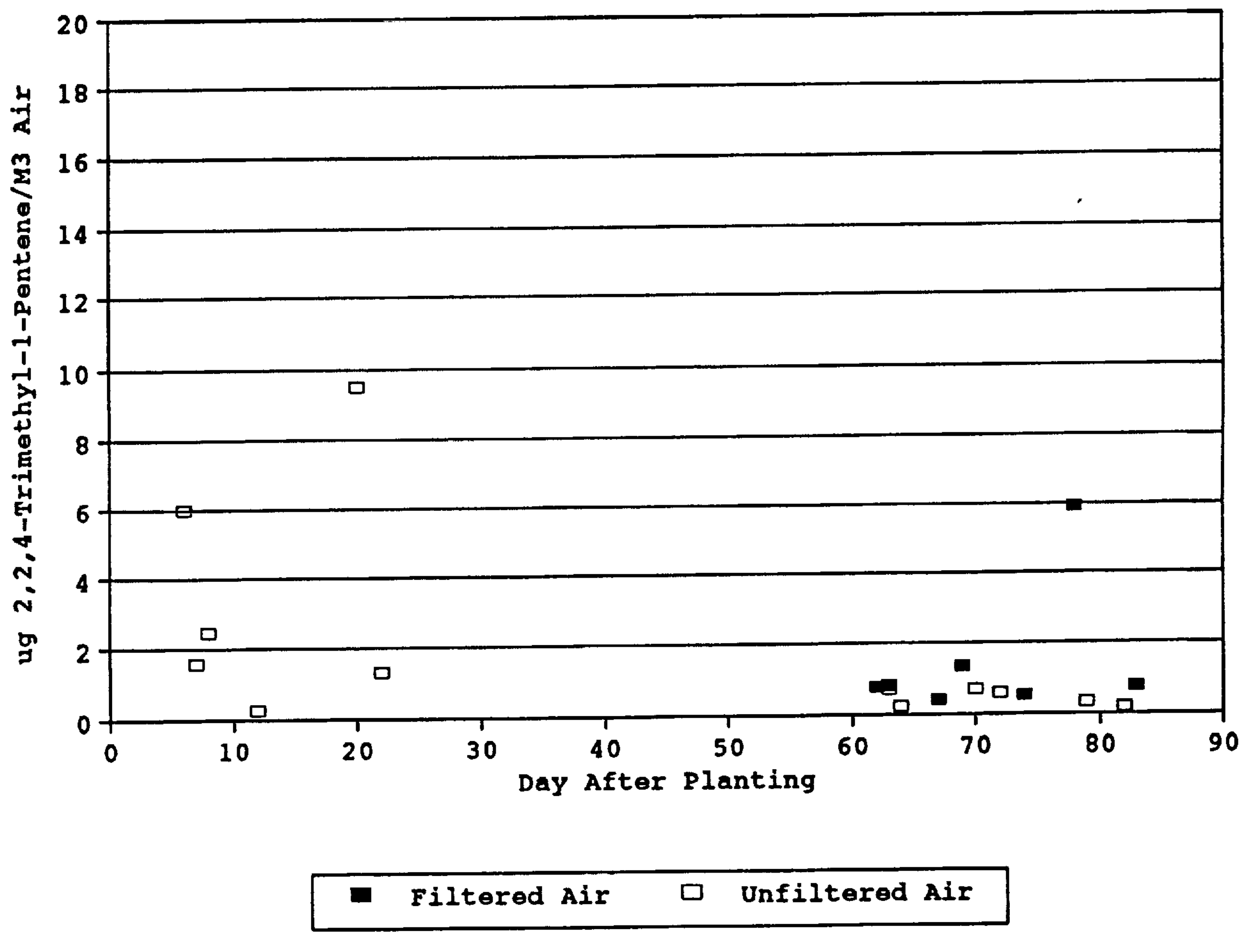


Figure 38. 2,2,4-Trimethyl-1-pentene Concentrations-Wheat Study(BWT931)



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NASA's Controlled Ecological Life Support System (CELSS) biomass production chamber at John F. Kennedy Space Center provides a test bed for bioregenerative studies using plants to provide food, oxygen, carbon dioxide removal, and potable water to humans during long term space travel. Growing plants in enclosed environments has brought about concerns regarding the level of volatile organic compounds (VOCs) emitted from plants and the construction materials that make up the plant growth chambers. In such closed systems, the potential exists for some VOCs to reach toxic levels and lead to poor plant growth, plant death, or health problems for human inhabitants. This study characterized the air in an enclosed environment in which wheat cv. Yocora Rojo was grown. Ninety-four whole air samples were analyzed by gas chromatography/mass spectrometry throughout the eighty-four day planting. VOC emissions from plants and materials were characterized and quantified.

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CELSS, air analysis, volatile organic compounds, wheat, gas chromatography/mass spectrometry

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