EFFECTS OF ENRICHED CARBON DIOXIDE AND OZONE STRESS ON CANOPY REFLECTANCE AND GRAIN YIELD IN WINTER WHEAT [1]

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ABSTRACT

An experiment was conducted during the spring of 1991 at USDA Beltsville Agricultural Research Center to evaluate the combined effect of carbon dioxide (CO_2) and ozone (O_3) on remotely sensed multispectral canopy reflectance and grain yields in winter wheat (Triticum aestivum L.). Plants were grown full-season (after dormancy to harvest) in the field in open-top chambers supplied with charcoal-filtered air (CF) or CF + 40 nl/l O_3 above ambient O_3 concentration (7 h/day, 5 day./week) having CO_2 concentration of ambient (350 μl/l) or +150 μl/l CO_2 (12 h/day). The resultant seasonal 7 h O_3 concentration was 19 nl/l and 79 nl/l O_3, for low and high O_3 treatments, respectively. Multispectral canopy reflectance was measured weekly from the early vegetative stages until maturation. The normalized difference vegetation index (ND), which was used to estimate the fraction of absorbed photosynthetically active radiation (FAPAR) and the absorbed PAR (APAR). Total final biomass and grain yield was obtained after harvest at physiological maturity. Tests of main effect of O_3 on ND was significant from the third week of treatment until maturation. Main effect of CO_2 on ND was not significant for all measurement dates. However, main effects of CO_2 and O_3 were significant for both biomass and grain yield. Accumulated APAR over the growing season was significantly lower for the high-O_3 treatments. Plants grown under CO_2 enriched air had significantly higher conversion efficiency (ϵ) of APAR into above ground dry biomass than plants grown under ambient CO_2 air. Conversion efficiency was significantly lower for the O_3 treatment with ambient CO_2 air. High-O_3 treatments had about 15 % less grain weight than low-O_3 treatments. Enriched CO_2 treatments had about 25 % more grain weight than ambient CO_2 treatments. Regression analysis showed that ND was responsible for up to 76% of the grain yield variation for winter wheat growing under the different air qualities.

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[1]Scientific Article N° A6334 and Contribution N° 8511
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INTRODUCTION

Studies of the relationship of canopy spectral reflectance of wheat and crop yield have been widely reported (Tucker, 1980; Pinter et al.,1981; Rudorff and Batista, 1990). Crop yield is the result of numerous environmental factors that affect plant growth and development and therefore canopy reflectance (Wiegand, 1984). Vegetation indices calculated from the reflectance of red (R_r) and near-infrared (R_{nir}) radiation, such as the normalized difference vegetation index (ND=$[R_{nir}-R_r]/[R_{nir}+R_r]$), are approximately linearly related to the fraction of absorbed photosynthetically active radiation (FAPAR)(Prince,1991). Daughtry et al. (1992) demonstrated that FAPAR can be estimated with ND data and that biomass production can be estimated as a function of accumulated absorbed PAR. These authors also pointed out that there is a linear relation between above ground dry biomass and accumulated absorbed PAR with different rates of above ground dry biomass production (efficiency conversion ϵ) for different crops (i.e., C_3 and C_4 crops).

Atmospheric CO_2 concentrations have increased over the past century from about 290 μl/l to 350 μl/l and an increase to levels of about 500 μl/l is expected by the end of the coming 20 to 30 years as a consequence of the world-wide growth in fossil fuel consumption (Wuebbles et al., 1989). An enriched CO_2 environment can cause C_3 plants to increase photosynthesis, and there by result in an increase in biomass, green leaf area duration and grain yield (Kurpa and Kickert, 1989). Near infrared radiation (700-1300 nm) is strongly scattered by vegetation and therefore highly dependent on the amount of biomass (Daughtry et al., 1992).

Ozone is among the most phytotoxic pollutants in the atmosphere and its formation and effects have been extensively investigated (Mulchi et al., 1986, 1988; Kurpa and Kickert, 1989). Ozone stress on wheat causes leaf injury, and a decrease in biomass and grain yield (Slaughter et al., 1989). Leaf reflectance in the visible wavelength is increased due to the decrease of PAR absorption by leaf pigments as a consequence of the injury to leaves caused by O_3 (Runeckles and Resh, 1975).

The objective of this study was to investigate the use of multispectral canopy reflectance data to estimate the effects on above ground biomass and grain yield in winter wheat grown in open-top chambers and exposed to enriched CO_2 and O_3 stress,

MATERIALS AND METHODS

A field study using open-top chambers was conducted at USDA Beltsville Agricultural Research Center, near Beltsville, Maryland in 1991. Winter wheat (cv. 'Massey') was covered after dormancy break in late March with 3 m diameter open-top chambers (Heagle et al., 1973). Atmospheric treatments consisted of two CO_2 (ambient, and + 150 μl/l CO_2) and two O_3 regimes (charcoal-filtered air (CF) and CF + 40 nl/l O_3 above ambient O_3 concentration) arranged in a 2x2 factorial design (RCB) with 4 replicates. The enriched CO_2 treatments were applied 12 h/day (06:00-18:00 EST), 7 days/week and the + 40 nl/l O_3 treatments were imposed 7 h/day (09:00-16:00 EST), 5 days/week from late March until early June.

Canopy reflectance was measured weekly, weather permitting, from early vegetative stages until maturation. A four band radiometer (Exotech model 100-BX) with a 15° field of view was used to measure reflectance factors (RF) in the following bands: 450-520, 520-600, 630-690, and 760-900 nm. An hand held boom was used to support the radiometer at about 2.3 m above the canopy. Four readings of approximately 0.3 m^2 of the canopy were taken for each chamber and RF was transformed to the normalized difference vegetation index (ND).

The fraction of absorbed PAR (FAPAR) was estimated from the linear relationship between ND and FAPAR reported by Daughtry et al., (1992) where:

$$FAPAR = -0.205 + 1.254\ ND \quad (1)$$

Incident PAR (PAR°) was obtained from a meteorological station close to the experimental site and absorbed PAR (APAR) was estimated:

$$APAR = FAPAR\ PAR_o \quad (2)$$

Incident PAR within the chambers may have been over estimated due to the fact that the incoming radiation is slightly attenuated by the plastic of the chamber walls.

Accumulated APAR was computed by the summation of the daily APAR obtained through intcrpolation from the close to weekly ND measurements throughout the crop growing season.

The conversion efficiency (ϵ) is the dry matter:radiation quotient or the dry matter production per unit of absorbed PAR (g/MJ):

$$\epsilon = \text{Above ground dry biomass} / \text{Accumulated APAR} \quad (3)$$

Total final above ground dry biomass and grain yield were determined from three 0.64 m^2 samples from each chamber following plant maturation in mid June.

RESULTS AND DISCUSSION

The seasonal 7-h average (09:00-15:00 EST) O_3 concentration for ambient air was 40 µl/l. The resultant 7-h averages for the high and low O_3 treatments were 79 µl/l and 19 µl/l, respectively.

The effects of CO_2 and O_3 on canopy reflectance measurements, transformed to the ND, are illustrated in Table 1. Significantly lower ND values for main effects on O_3 (79 nl/l) were observed from day of year 106 on, which was coincident with the first visual symptoms of O_3 injury on leaves in the O_3 treated chambers. The lower NDs observed in the high-O_3 treatments are likely the combined result of an increase in the reflectance in the red waveband caused by lower absorption of the incoming PAR by the leaf pigments and the lower near infrared canopy reflectance due to a significant decrease

Table 1

Summary of main and simple effects of CO_2 and O_3 treatments on the normalized vegetation index (ND) for measurement dates 1 to 11.

Chamber Treatments		D A Y O F Y E A R										
CO_2	O_3	92 (ND-1)	94 (ND-2)	100 (ND-3)	106 (ND-4)	113 (ND-5)	121 (ND-6)	126 (ND-7)	132 (ND-8)	136 (ND-9)	144 (ND-10)	151 (ND-11)
CO_2 Treatment Means												
Ambient	-	0.888	0.910	0.940	0.927	0.912	0.910	0.909	0.886	0.866	0.814	0.606
+150 µl/l	-	0.888	0.910	0.941	0.934	0.926	0.916	0.916	0.895	0.881	0.837	0.557
Statistical significance												
O_3 Treatment Means												
-	CF	0.889	0.909	0.940	0.936	0.939	0.934	0.925	0.903	0.887	0.851	0.618
-	CF+O_3	0.887	0.911	0.940	0.926	0.889	0.893	0.899	0.878	0.859	0.800	0.566
Statistical significance					*	**	**	**	**	**	**	
CO_2 and O_3 Treatments												
Ambient	CF	0.893	0.909	0.940	0.935^{a}	0.937^{a}	0.934^{a}	0.925^{a}	0.903^{a}	0.885^{a}	0.848^{a}	0.635
	CF+O_3	0.883	0.910	0.940	0.919^{b}	0.888^{b}	0.887^{b}	0.892^{b}	0.869^{b}	0.846^{b}	0.781^{b}	0.578
+150 µl/l	CF	0.886	0.908	0.941	0.936^{a}	0.941^{a}	0.933^{a}	0.925^{a}	0.903^{a}	0.889^{a}	0.854^{a}	0.601
	CF+O_3	0.890	0.912	0.941	0.932^{ab}	0.910^{b}	0.899^{b}	0.906^{ab}	0.888^{ab}	0.872^{ab}	0.820^{a}	0.553
LSD	($p<0.05$)	0.050	0.035	0.012	0.014	0.027	0.028	0.022	0.023	0.030	0.036	0.105

* , ** significantly different at the 5% and 1% probability level, respectively.

(11%) observed in the final dry biomass (Table 2). Main effects of CO_2 on ND were not significant for any measurement date. However, dry biomass was significantly higher (15%) for the high-CO_2 treated plants (Table 2). The lack of significance for the high-CO_2 treatments in terms of the ND may be attributed to the fact that the canopy reflectance in the near infrared was already close to saturation in the ambient-CO_2 treatments and therefore no significant increase in near infrared waveband could be achieved for the high-CO_2 treatments.

Changes in the fraction of absorbed PAR (FAPAR) as estimated from the ND data using a linear transformation (Eq. 1) are illustrated in Figure 1. Analyses of variance for FAPAR provided the same significance levels observed for ND since both are very closely related.

The absorbed PAR (APAR) was estimated from daily FAPAR and daily incident PAR (Eq. 2) and integrated over the growing season from early vegetative stage to maturation to obtain an estimate of the accumulated APAR. No significant difference was found for the main effect of the CO_2 factor for accumulated APAR, even though significantly higher dry biomass was observed for the enriched CO_2 treatments (Table 2). The O_3 factor significantly reduced the cumulative APAR because less radiation was absorbed by plants grown under high-O_3 (Table 2).

Table 2

Summary of main and simple effects of CO_2 and O_3 treatments on grain yield, dry biomass, harvest index, cumulative APAR and conversion efficiency.

Chamber Treatments CO_2	O_3	Grain Yield (g/m^2)	Dry Biomass (g/m^2)	Harvest Index (%)	Cum. APAR (MJ/m^2)	Conv. Effic. (g/MJ)
CO_2 Treatment Means						
Ambient	-	476	1392	34.1	414	3.36
+150 µl/l	-	600	1606	37.4	418	3.82
Statistical significance		**	**	**	ns	**
O_3 Treatment Means						
-	CF	582	1583	36.8	425	3.73
-	CF+O_3	494	1415	34.7	408	3.45
Statistical significance		**	**	**	**	**
CO_2 and O_3 Treatments						
Ambient	CF	538^b	1513^a	35.6^a	425^a	3.54^b
	CF+O_3	414^c	1272^b	32.5^b	403^b	3.13^c
+150 µl/l	CF	627^a	1653^a	37.9^a	425^a	3.91^a
	CF+O_3	574^{ab}	1559^a	36.9^a	412^{ab}	3.77^{ab}
LSD	(p=0.05)	58	156	3.1	15	0.28

*, ** significantly different at the 5 % and 1% probability level, respectively.

Plants grown under enriched CO_2 conditions exhibited a significantly higher conversion efficiency (ϵ) than plants grown under ambient CO_2 (Table 2) even though their accumulated APAR values were not responsive to CO_2. Significantly lower ϵ values were found in response to the high O_3 treatments which were consistent with the reductions in both dry biomass and accumulated APAR. The reduction in ϵ in response to O_3 stress may also be attributed to the portion of the PAR_o striking dead leaf tissue not being converted to dry matter and reduction in photosynthesis in living tissue (Mulchi et al., 1992)

Main effects of CO_2 and O_3 on grain yield (Table 2) were highly significant for both. The high-CO_2 treatments produced 26% more grain than ambient-CO_2 treatments and the high O_3 treatments produced 15% less yield than the low-O_3 treatments. However, in the absence of O_3 stress, plants grown in the enriched CO_2 environment exhibited a 16 % increase in grain yield and plants grown under ambient CO_2 levels and exposed to O_3 showed a 23 % decrease in grain yield. In the presence of the high CO_2 level, exposure to O_3 stress caused a 8 % reduction in grain yield. Therefore, high CO_2 treatment would appear to counteract the negative impact of O_3 stress on wheat as was also observed with soybean (Mulchi et al., 1992). Simple effects of CO_2 produced lower dry biomass and harvest index, but the differences were not significant. Tests for the interactive effect of CO_2 and O_3 were not significant in any of the analysis of variance.

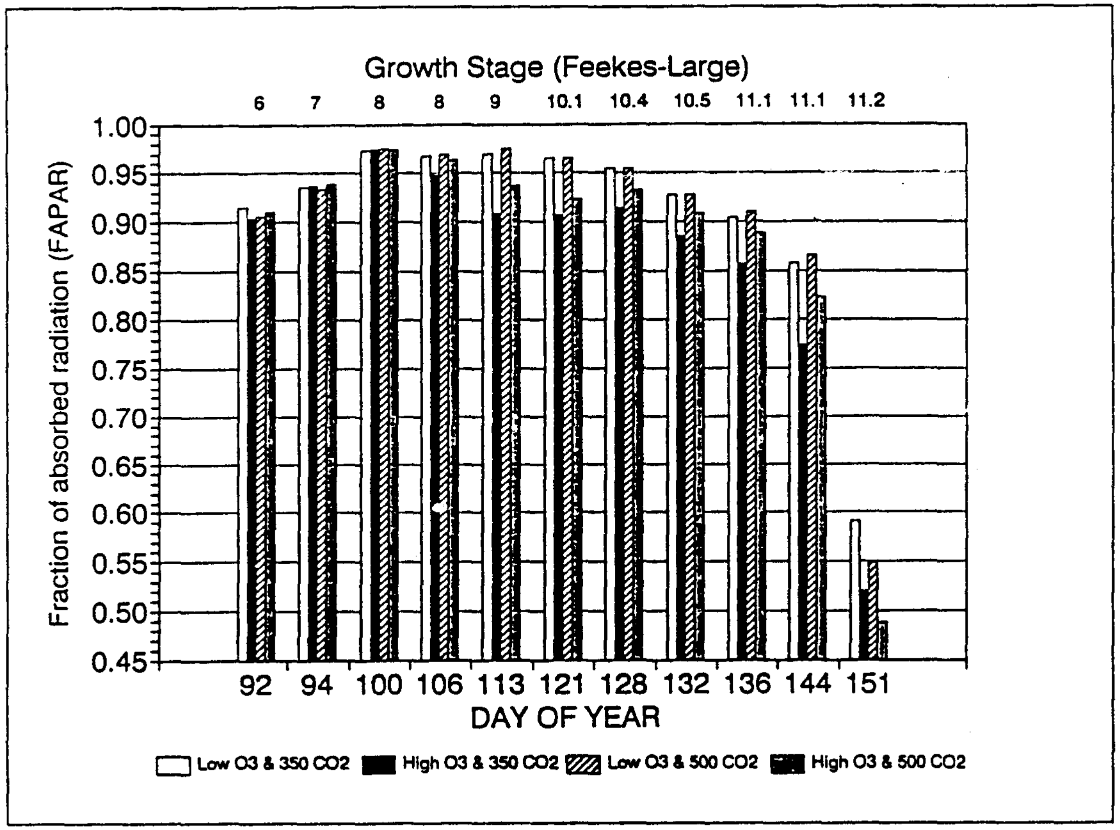

Figure 1 - Simple effects of O_3 and CO_2 on the fraction of absorbed PAR (FAPAR) throughout the winter wheat growing season.

Regression equations were obtained using ND and grain yield data for replicates 1 and 2. These equations were then used to estimate the grain yield for replicates 3 and 4. Representative results from these analysis are presented in Table 3. Due to the relatively high correlation among NDs, regression coefficients seem to be unstable if more than two NDs are used in the equation. Using single ND obtained between stages 10.4 and 11.1, a grain yield variation of 50% to 76% was explained by the ND.

Table 3

Best regression equations for the relationship of grain yield (Y_{obs}) vs. normalized difference vegetation index (ND) using replicates 1 and 2 (n=8) and coefficient of determination (r^2) for (Y_{obs}) for replicates 3 and 4 (n=8) vs. estimated grain yield (Y_{est}) from the regression equations.

Growth Stage (Feekes & Large)	Regression Equations	r^2	
		Y_{obs} vs. ND	Y_{obs} vs. Y_{est}
10.1	Y_{est}=- 977+1688ND6	0.33	0.47
10.4	Y_{est}=-1688+2448ND7	0.30	0.66
10.5.2	Y_{est}=-1650+2478ND8	0.32	0.76
11.1	Y_{est}=-2067+2997ND9	0.56	0.65
11.1	Y_{est}=-1015+1884ND10	0.77	0.50
8 & 11.1	Y_{est}=-1351+ 407ND4+1834ND10	0.77	0.54
11.1 & 11.1	Y_{est}=-1097+ 165ND9+1809ND10	0.77	0.52
8, 10.1 & 11.1	Y_{est}=-3384+4162ND4-2406ND6+2714ND10	0.87	0.72
9, 10.4 & 11.1	Y_{est}=- 521+ 245ND5- 968ND7+2079ND10	0.78	0.46
8, 10.4 & 11.1	Y_{est}=-2126+3305ND4-2604ND7+2377ND10	0.83	0.63
8, 10.4, 11.1 & 11.1	Y_{est}=-2543+3670ND4-3468ND7+1309ND9+2037ND10	0.85	0.70

CONCLUSIONS

1) High-O_3 treatments (79 nl/l) significantly reduced spectral canopy reflectance (ND) after the first visual symptoms of O_3 injury appeared on leaves;

2) Accumulated APAR was significantly reduced for the high-O_3 treatments, but no difference was found for the enriched CO_2 treatments;

3) High-O_3 and high-CO_2 treatment (79 nl/l O_3 and 500 µl/l CO_2) showed a trend of lower NDs over the growing season, but higher final dry biomass and grain yield were observed when compared to the control treatment (19 nl/l O_3 and 350 µl/l CO_2);

4) Single ND obtained between heading (stage 10.1) and maturation (stage 11.1) explained from 50% to 76% of the observed grain yield variation.

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