The residual effects of bensulfuron-methyl on growth and photosynthesis of soybean and peanut


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Abstract

The effects of various concentrations of bensulfuron-methyl residues (BSM, 0–500 µg kg⁻¹) on the growth and photosynthesis of soybean and peanut were studied. Shoot length, root length, root-to-shoot ratio, and biomass of soybean and peanut seedlings declined with the increase of BSM residue concentrations. As the concentration of BSM increased, SPAD value, net photosynthetic rate, stomatal limitation, stomatal conductance, and transpiration rate also declined with varying extent, but dark respiration rate and intercellular CO₂ concentration increased gradually. PSII maximum quantum yield, actual quantum yield, and electron transport rate were significantly reduced by the BSM residues in soil, and the reduction was mostly attributed to the decrease in photochemical quenching coefficient. The results showed that photosynthesis in both crops was limited by nonstomatal factors. The residues of BSM caused reversible damage in PSII reaction centers and decrease the proportion of available excitation energy used for photochemistry.

Additional key words: Arachis hypogaea; chlorophyll fluorescence; gas exchange; Glycine max (Linn.) Merr.; phytotoxicity; relative chlorophyll content.

Introduction

Bensulfuron-methyl [BSM, 2-(4,6-dimethoxypyrimidin-2-carbamoysulfamoyl)-o-toluic acid methyl ester], discovered by the DuPont Co. in the late 1970s, is a type of sulfonylurea herbicide, characterized by broad-spectrum weed control at very low use rates (30–100 g ha⁻¹), high herbicidal activity, good crop selectivity, and low mammalian toxicity (Brown 1990, Brusa et al. 2001, Sabater et al. 2002). All these characteristics make sulfonylurea herbicides such as BSM an ideal substitute for other older herbicides (Pimentel et al. 1991). The use of BSM in southeast China, California, Japan, and many other areas in the world as a herbicide in rice paddies has steadily increased over the past several years (Sarmah et al. 1998, Sabater et al. 2002), making great contributions to crop protection and production. However, BSM is neither particularly volatile nor photodegradable (Boschin et al. 2003, Si et al. 2004) and therefore may persist for a long time (over 100 d) when applied under specific climatic and/or soil conditions (Blair and Martin 1998) and can be leached into the environment or its residues may damage other crops in the rotation (Si et al. 2004).

Crop rotation is common in China. For example, in most wheat-growing areas of the country, wheat is rotated with peanut, soybean, etc. Over large cultivated tracts in southern China, farming is even more intensive and consists of three crops a year: wheat, rice, and soybean (in autumn, after rice). In some areas in the south, owing to recent droughts, a rotation of rice with peanut has been promoted vigorously to boost the production of food grains as well as of edible oil.

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Abbreviations: ALS – acetolactate synthase; a.i. – active ingredient; BSM – bensulfuron-methyl; Chl – chlorophyll; Cᵢ – intercellular CO₂ concentration; E – transpiration rate; ETR – electron transport rate; Fₘ – maximum fluorescence yield of the dark-adapted state; F₀ – minimal fluorescence yield of the dark-adapted state; Fᵥ – variable fluorescence; Fᵥ/Fₘ – maximum quantum yield of PSII photochemistry; gₛ – stomatal conductance; Lₛ – stomatal limitation; LSD – least significant difference; Pₙ – net photosynthetic rate; qₚ – photochemical quenching coefficient; R:S – root-to-shoot ratio; SDM – shoot dry mass; RD – root dry mass; SD – standard deviation; TDM – total dry mass; ΦPSII – the actual quantum yield of PSII.
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A great deal of research has been conducted on the adsorption, degradation, and leaching of BSM in soils and its photolysis on soil surface (Saeki and Toyota 2004, Si et al. 2004, Zhu et al. 2005, Luo et al. 2008, Lin et al. 2010, Lin et al. 2012), including the residual phytotoxicity of sulfonylureas to rotation crops, such as maize, sunflower, sugar beet, and dry beans (Anderson and Humburg 1987, Curran et al. 1991). Zhang et al. (2016) reported that residual BSM mainly affected plant height, leaf width, and the activity of amylase and peroxidase, but had little effect on the physiological activity in tobacco. Ye et al. (2005) found that residual BSM inhibited root length in rape. Su et al. (2016) reported that plant height, root length, and net photosynthetic rate of maize seedlings decreased with increased concentrations of BSM residue.

BSM acts by inhibiting the enzyme acetolactate synthase (ALS), which is involved in the synthesis of branched-chain amino acids, leading to the cessation of cell division and of subsequent growth processes in plants. Although photosynthesis is not a major target of herbicides, which inhibit ALS, changes in photosynthesis parameters were detected in plants treated with herbicides (Sousa et al. 2014). Xia et al. (2006) found that these parameters were inhibited to various degrees upon imazaquin application. Sousa et al. (2014) reported that the organs of photosynthesis in rice may be damaged before visible injury by imidazolinone, lowering the photosynthesis capabilities of the crop. Tomar et al. (2015) reported that anthracene lowered the performance index of PSII in soybean significantly. Imazapic residues in soil inhibited the growth of wheat seedlings and significantly reduced the rate of photosynthesis in wheat (Su et al. 2013).

Although some information is available on the toxicity of sulfonylurea herbicides to weeds and crops (French and Buckley 2008, Kleter et al. 2011, Muszynski et al. 2014), the toxic effects of BSM residues on soybean and peanut have hardly been investigated. In order to fill this research gap, the objective of this study was to understand the response of soybean and peanut to BSM residue by assessing its potential phytotoxicity through examining photosynthesis characteristics so as to provide a theoretical basis for practical use of BSM in rice or wheat rotations.

Materials and methods

Plant material and herbicide: The soil used in this study was the top soil (0–10 cm) collected from Yuanyang, in Henan province, China. The soil (pH 8.4, soil:water ratio of 1:2.5, w/v), which contained 5.5 g(organic matter) kg⁻¹, 29.8 mg(available N) kg⁻¹, 6.5 mg(available P) kg⁻¹, and 78.3 mg(available K) kg⁻¹ – measured according to the method described by Bao (2000) – was air-dried and passed through a 2-mm sieve to remove debris and stones.

Soybean (Glycine max (Linn.) Merr., cv. Xudou 18) and peanut (Arachis hypogaea, cv. Yuhua 15) were selected as the test species. Seeds of soybean and peanut were pregerminated for 24 h at 25°C prior to sowing by placing the seeds in Petri dishes on wet paper towels and keeping the dishes in darkness. BSM (98.5% pure) was purchased from Hangzhou Tianyi Pesticide Manufactory, Zhejiang province, China.

Soil treatment and culture conditions: Stock solutions of BSM were prepared by placing a known quantity of BSM in approximately 50 mL of acetone and then diluting with water to the 1-L mark in a volumetric flask (Eliason et al. 2004). Standard solutions were created from the stock solutions to produce solutions with concentrations of 0.5, 1.5, and 2.5 mg of active ingredient (a.i.) L⁻¹(BSM). Soil samples (each 200 g) were placed into pots (70 mm tall and 83 mm in diameter) and 40 mL of the standard solution was added to the untreated soil to produce concentrations of BSM up to two or four times those achieved by following the recommended field application rate [74 (µg(a.i.) kg⁻¹)]. This resulted in concentrations of 100, 300, and 500 (µg(a.i. of BSM) kg⁻¹(soil)). Throughout the paper, the concentrations of BSM was referred to the concentrations of its active ingredient. For the control, 50 mL of distilled water was added to the untreated soil. The soil samples were then manually mixed to ensure uniform distribution of the added BSM throughout the soil and allowed to equilibrate for 24 h. Three pregerminated seeds of soybean or two of peanut, of similar size and comparable length of the radicle, were selected and placed onto the soil surface and covered with a small amount of soil (a layer approximately 0.5 cm thick), which was lightly packed. The pots were watered daily to 20% of soil moisture content by adding distilled water to reach a pre-determined mass. The seedlings were grown in a growth chamber under controlled conditions [12 h of light at 27°C alternating with 12 h of darkness at 25°C; light intensity of 150 µmol(photon) m⁻² s⁻¹; relative humidity of 70–75%].

Growth parameters: After 14 d of growth, plant height and root length of soybean and peanut seedlings were measured and recorded. Each plant was separated into its roots and shoots. These samples were placed in an oven at 80°C for 48 h before the dry mass of each seedling component was recorded. The root-to-shoot ratio (R:S) was calculated from the shoot dry mass (SDM) and root dry mass (RDM), total dry mass (TDM) being the sum of RDM and SDM.

Relative chlorophyll (Chl) content and gas exchange: After 14 d, five to ten successive readings (depending on the area) in SPAD units were taken by a Chl meter SPAD-502 (Konica Minolta Camera Co. Ltd., Japan) across the whole surface of leaves, taking one leaf at a time. Net photosynthetic rate (Fₜₙ), stomatal conductance (gₛ), intercellular CO₂ concentration (Cᵢ), and transpiration rate (E) of single leaves were measured from the central part of
Relative Chl content and gas exchange: SPAD readings have been shown to be strongly correlated to leaf Chl content (Marquard and Tipton 1987, Markwell et al. 1995, Wang et al. 2004). At a low residue concentration of BSM (100 µg kg⁻¹), SPAD values of soybean and peanut seedling leaves were significantly lower than those in the control, the extent of decrease being 13 and 18%, respectively. As the BSM residue concentration increased, SPAD values decreased even further: the decrease at 300 and 500 µg kg⁻¹ in soybean was 19 and 24%, respectively; in peanut, the corresponding values were 29 and 30% (Fig. 3E).

As the residue concentration of BSM increased, PN decreased significantly in both soybean and peanut in all the treatments (Fig. 2D), compared with the control: the extent of decrease was 38–62% in soybean and 22–52% in peanut.

The application of BSM increased Ci to varying degrees in soybean and peanut (Fig. 2C). Compared with the control, Ci in soybean was not significantly different at 100–300 µg kg⁻¹ but increased significantly at 500 µg kg⁻¹; Ci of peanut leaves at 100, 300, and 500 µg kg⁻¹ increased significantly, by 28, 31, and 38%, respectively.

Concerning Le, its value decreased in both crops as the residue concentration of BSM increased (Fig. 2D). Although the difference between soybean and the control was not significant at 100 µg kg⁻¹, the differences were significant at 300–500 µg kg⁻¹. In peanut, the decrease was not significant at 100–300 µg kg⁻¹ but it was significant at 500 µg kg⁻¹ (the extent of decrease was 33%). Thus, the pattern of changes in Le in the two species was just the opposite of that seen in Ci.
As the residue concentration of BSM increased, $g_s$ of soybean leaves decreased. The difference in $g_s$ between the treated plants and the control was not significant at 100 µg kg$^{-1}$ but it was significant at 300 and 500 µg kg$^{-1}$. Compared with the control, $g_s$ of peanut leaves in 100, 300, and 500 µg kg$^{-1}$ decreased by 40, 52, and 74%, respectively (Fig. 2E).

As shown (in Fig. 2F), $E$ decreased significantly in both crops as the residue concentration of BSM increased. The decrease at 100, 300, and 500 µg kg$^{-1}$ in soybean was 40, 56, and 58%, respectively; in peanut, the corresponding values were 30, 53, and 67%. The pattern of changes in $E$ in each crop thus essentially matched to that in $g_s$, which also suggests that BSM affected photosynthesis in soybean and peanut significantly.

**Discussion**

Herbicide persistence is an important fact in crop production since residues can potentially injure sensitive crops grown in rotation (Riddle et al. 2013). A laboratory test helps to predict potential herbicide residue problems

**Chl fluorescence** parameters, such as $F_v/F_m$, $\Phi_{PSII}$, $q_P$, and ETR in both crops decreased as the residue concentrations of BSM increased (Fig. 3A–D). Compared with the untreated controls, $F_v/F_m$ and $\Phi_{PSII}$ of soybean leaves at 100–500 µg kg$^{-1}$ decreased by 2–6% and 16–28%, respectively, $q_P$ and ETR at 300 and 500 µg kg$^{-1}$ were also significantly lower, by 13–18% and 24–25%, respectively. In peanut, $F_v/F_m$ was significantly lower at 300–500 µg kg$^{-1}$ by 1–2%, $\Phi_{PSII}$ decreased significantly at 100–500 µg kg$^{-1}$ by 4–7%, and $q_P$ and ETR were significantly lower only at 500 µg kg$^{-1}$ by 8%. These results showed that fluorescence parameters of soybean were more sensitive than those of peanut to BSM residue.
so that proper decisions can be taken about crop rotation, herbicide selection, planting date, and other cultural practices. In the present study, the residue of BSM lowered plant height and root length in both soybean and peanut significantly, the extent of decrease being directly proportional to the concentration of BSM added to the soil. Roots proved to be more sensitive to the residue of BSM than shoots, probably because the seedlings absorbed it through their roots and then transported it to the stems and leaves. As the concentration of the residual BSM increased, SDM, RDM, and TDM declined gradually. The root-to-shoot ratio in both soybean and peanut decreased as BSM concentration increased, showing that BSM had a greater effect on below-ground biomass than on above-ground biomass. These results agree with analysis of Lou et al. (2005) that BSM inhibition of root length is greater than that of plant height. Our results showed that BSM residue strongly inhibited the growth of soybean and peanut seedlings, and that soybean was more sensitive to BSM residue.

Stress factors, such as temperatures too high or too low, insufficient light, and heavy metals are known to affect photosynthesis (Berry and Bjorkman 1980, Burzyski and Klobus 2004, Kosobrukhov et al. 2004, González-Naranjo et al. 2015, Tomar et al. 2015). Some herbicides can also affect the growth and development of crops by impairing

![Fig. 2](image_url)
normal physiological parameters or functions. For example, flumioxazin can cause a sharp drop in \( P_N \) and \( g_s \) in grapes (Bigot et al. 2007). Leaf SPAD values are a direct reflection of the relative leaf Chl and are positively correlated to Chl content. Chl content is closely related to \( P_N \), and herbicides have been shown to reduce the content of photosynthetic pigments and \( P_N \) in leaves (Su et al. 2013). Both \( P_N \) and Chl content showed a similar trend, and the decrease in Chl might also be one of the major reasons for the decrease in \( P_N \) in the present experiment. The decrease in \( P_N \) and the increase in \( R_D \) in both the crops suggest that increased respiration could be a mechanism to alleviate the damage to photosynthesis caused by BSM (Catriona et al. 2002, Ohe et al. 2005, Sun et al. 2010).

Farquhar and Sharkey (1982) examined whether stomatal or nonstomatal factors were the main cause of reduced \( P_N \) as can be judged by the changing pattern of both \( C_i \) and \( L_s \). If both \( C_i \) and \( P_N \) decreased, accompanied by an increase in \( L_s \), the decrease of \( P_N \) was mainly caused by stomatal limitation. On the contrary, when \( P_N \) decreased, \( C_i \) may increase or be constant despite lower \( g_s \), and is accompanied by a decrease in \( L_s \). Thus it is the photosynthetic activity of mesophyll cells rather than \( g_s \) that was regarded as the critical factor in reducing \( P_N \).

According to the above theory, the residual effects of BSM resulted in decreased \( P_N \) and \( L_s \) and increased \( C_i \), indicating that photosynthesis in both crops was limited by nonstomatal factors. These results were consistent with earlier findings showing that the suppression of \( P_N \) induced by cyazofamid was mostly due to nonstomatal factors (Xia et al. 2006).

In order to further investigate the nonstomatal factors involved, Chl fluorescence parameters were analyzed. Chl fluorescence is a major technique for detecting and analyzing photosynthesis, which can provide a wealth of information on the photosystem and the electron transfer activities (Krause and Weis 1991). Earlier studies have shown that herbicides damage the PSII complex, block photosynthetic electron transfer, reduce \( F_{v}/F_{m} \), \( \Phi_{PSII} \), and \( q_P \) significantly, and increase the nonphotochemical quenching coefficient in wheat leaves (Wang et al. 2011). The residual BSM caused significant decreases in \( F_{v}/F_{m} \),

Fig. 3. (A) Maximum quantum yield of PSII photochemistry \( (F_{v}/F_{m}) \), (B) actual quantum yield of PSII under actinic light of 150 µmol (photon) m\(^{-2}\) s\(^{-1}\) \( (\Phi_{PSII}) \), (C) photochemical quenching coefficient \( (q_P) \), (D) electron transport rate \( (ETR) \), (E) SPAD value of soybean and peanut seedlings under different soil concentrations (0, 100, 300, and 500 µg kg\(^{-1}\)) for the herbicide bensulfuron-methyl. Error bars show standard deviation \( (n = 4) \). Different letters on the bars indicate significant differences at \( P<0.05 \), according to Duncan’s multiple range test.
Parameters indicate that the residues of BSM caused reversible destruction in PSII reaction centers. A decrease in qP indicated a higher proportion of closed PSII reaction centers, i.e., an increase in the proportion of the reduced state of QA, which probably leads to a decrease in the proportion of available excitation energy used for photochemistry (Genty et al. 1989). Dayan and Zaccaro (2012) observed a decreased ETR in cucumber plants exposed to light and bentazon. An increase in the non-photochemical quenching coefficient was observed concomitantly with a drop in ΦPSII, qP, and ETR, confirming that the energy absorbed by the antenna system was not used for photochemical effect in photosynthesis (Maxwell and Johnson 2000, Müller et al. 2001, Roháček 2002).

The accumulation of biomass represents the net effect of carbon assimilation and maintenance. In soybean and peanut, the SDM, RDM, and TDM were significantly reduced by BSM residue concentration, suggesting that growth of was negatively influenced by BSM residue.

References


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