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Herbicide Clomazone Does Not Inhibit *In Vitro* Geranylgeranyl Synthesis from Mevalonate[1]

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ABSTRACT

Clomazone reduced the chlorophyll and carotenoid contents of spinach (*Spinacia oleracea* L.), barley (*Hordeum vulgare* L.), velvetleaf (*Abutilon theophrasti* Medik.), and soybean (*Glycine max* L. Merr.) seedlings. The order of species sensitivity was velvetleaf > spinach > barley > soybean. Clomazone (100 micromolar) did not affect the *in vitro* activities of spinach isopentenyl pyrophosphate isomerase or prenyl transferase. Clomazone also did not affect the synthesis of isopentenyl pyrophosphate from mevalonic acid. Thus, clomazone had no direct *in vitro* effect on the synthesis of geranylgeranyl pyrophosphate from mevalonic acid. Greening seedlings of both soybean and velvetleaf metabolized clomazone. No qualitative differences in the metabolites were detected between soybean and velvetleaf. Thus, differential metabolism of clomazone to a toxic chemical that inhibits terpenoid synthesis is unlikely. Clomazone has either a mode of action not yet identified or a metabolite that is selective in that it is much more active in sensitive than tolerant species.

Clomazone[4] is a selective herbicide used in soybean for the control of certain grass and broad-leaved weeds. Because differences in the rate of clomazone metabolism by clomazone-tolerant and -susceptible species have not accounted for selectivity (14, 18–21), differing sensitivities of the clomazone target site among species has been speculated to be responsible for its selective action (14, 19–21). After the target for clomazone is determined, the susceptibility of that site in tolerant and susceptible species would be experimentally addressable.

The phytotoxic effects of clomazone cause susceptible plants either to have reduced levels or be completely devoid of plastid pigments (6). Several *in vivo* (6, 14, 15) and *in vitro* (16) observations have led to the conclusion that clomazone inhibits the formation of plastid terpenoids by interfering with the early steps of isoprenoid biosynthesis between MVA and geranylgeranyl pyrophosphate. Specifically, spinach IPP isomerase or prenyl transferase have been speculated to be the inhibition site(s) for clomazone (16). However, recent results have suggested that IPP isomerase and prenyl transferase in wild mustard and daffodil chromoplasts are insensitive to clomazone (12). The reason for the discrepancy between the results from spinach and wild mustard or daffodil chromoplasts is unknown. In the spinach study, MVA was used as the terpenoid substrate, whereas in the latter study IPP was the substrate used. The importance of this difference in the results is unknown. Therefore, the objective of this research was to determine whether clomazone directly inhibits terpenoid synthesis in spinach plants. Specifically, clomazone inhibition of spinach IPP isomerase-, prenyl transferase-, and IPP-synthesizing enzymes from MVA was studied to test the effect of clomazone on terpenoid synthesis. Additional experiments comparing clomazone metabolism by young seedlings of tolerant and susceptible species were conducted to evaluate clomazone bioactivation by greening tissues as another possible mechanism of clomazone selectivity.

MATERIALS AND METHODS

Chemicals

Analytical clomazone and [^{14}C]methylene-clomazone were provided by FMC Corp. [1-^{14}C]IPP (56 mCi/mmol) and [^{14}C]MVA (54.9 mCi/mmol) were purchased from Amersham Co.

Sensitivity of Seedlings to Clomazone

Relative sensitivities of spinach (*Spinacia oleracea* L.), barley (*Hordeum vulgare* L.), velvetleaf (*Abutilon theophrasti* Medik.), and soybean (*Glycine max* L. Merr.) seedlings to clomazone were determined by measuring the effect of clomazone on Chl and carotenoid contents of either the cotyledons or the first foliage leaf of each species. Seeds were planted in vermiculite and watered with aqueous solutions of 0, 0.1, 1, 10, or 50 μM clomazone. Seedlings were grown in a greenhouse (24°C day, 20°C night) with supplemental illumination (800 μE) and harvested 7 d after planting. Cotyledons or first foliage leaves were homogenized in 80% (v/v) acetone. Homogenates were centrifuged at 10,000*g* for 10 min. Absorbance values of supernatants at 663.2, 646.8, and 470 nm and the equations of Lichtenthaler (11) were used to determine total Chl and total carotenoid contents.

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[4] Abbreviations: clomazone, 2-[(2-chlorophenyl)methyl]-4,4-dimethyl-3-isoxazolidinone; MVA, mevalonic acid; MVAP, mevalonate-5-phosphate; MVAPP, mevalonate-5-diphosphate; IPP, isopentenyl pyrophosphate; HMG-CoA, 3-hydroxy-3-methylglutaryl coenzyme A; LSS, liquid scintillation spectrometry.

Chloroplast Isolation

Chloroplasts from spinach plants were isolated according to the procedure of Mullet and Chua (13) with minor modifications. Spinach tissue (25 g) was homogenized in 100 mL buffer (50 mM Hepes-KOH [pH 7.5], 300 mM sorbitol, 1 mM $MgCl_2$, 1 mM $MnCl_2$, 2 mM EDTA, 5 mM isoascorbate, 20 μM leupeptin) in a Sorvall Omnimixer with five 3-s bursts at full speed at 4°C. The homogenate was filtered through six layers of cheesecloth and centrifuged at 3000*g* for 3 min to give the crude chloroplast pellet. The supernatant was quickly discarded, and the pellet was gently resuspended in 10 mL of homogenization buffer and layered onto a preformed linear Percoll gradient. The gradient was formed by combining 30 mL of 2× homogenization buffer with 30 mL of Percoll and centrifuging at 25,000*g* for 60 min in a Beckman SW-27 rotor. The resuspended, crude chloroplasts were layered on top of the gradient. Intact chloroplasts were isolated in the Percoll gradient by centrifugation for 8 min at 14,600*g*. The lower band of chloroplasts (intact chloroplasts, approximately 5 mL) was collected, and these chloroplasts were washed twice by resuspending in 20 mL of homogenization buffer and centrifuging at 3000*g* for 3 min. The final resuspended pellet, consisting of intact chloroplasts as judged by visual inspection using phase contrast microscopy, was stored on ice in the dark until used. Chl was determined by the method of Arnon (1). Chloroplasts were osmotically shocked by resuspending in 20 mM Hepes-KOH (pH 7.5), 1 mM $MgCl_2$, and 1 mM $MnCl_2$ before use in the terpenoid synthesis assay. This osmotic shock procedure ensured the free passage of IPP and inhibitors through the chloroplast envelope (4).

Terpenoid Synthesis Assay

Conversion of IPP (water soluble; acid stable) to geranylgeraniol derivatives (lipid soluble; acid labile) was measured (4). The reaction mixture (0.5 mL) contained 20 mM Hepes-KOH (pH 7.5), 1 mM $MgCl_2$, 1 mM $MnCl_2$, 10 mM KF, 15 μM [1-^{14}C]IPP, and known amounts of osmotically shocked chloroplasts. Clomazone (100 μM) and iodoacetamide (5 mM) were tested as inhibitors. Incubation was in the dark for 30 min at 25°C. The reaction was terminated by addition of 1 mL of methanol. Reaction products were hydrolyzed by addition of 100 μL of 10 N HCl and incubation at 37°C for 20 min. Acid-labile products were extracted with 4 mL of petroleum ether (boiling point, 40 to 60°C). Radioactive content of 0.5-mL aliquots of the extract was determined by LSS. Terpenoid synthesis was expressed as nanomoles of substrate converted to acid-labile products per milligram Chl per hour.

Terpenoid alcohols and/or the corresponding tertiary allylic rearrangement products (linalool, nerolidol, and geranylinalool) produced by the hydrolysis with HCl were separated by TLC. Silica gel plates were impregnated with paraffin oil by dipping the plates in a solution of 5% (v/v) paraffin oil in petroleum ether. The developing system was methanol:water (80:20, v/v) (16). Locations of geraniol, farnesol, and phytol standards were determined by staining with iodine vapors. Radioactive contents of products were determined after scraping zones of silica gel off the plate and into scintillation vials. TLC plates were scrapped while still wet to avoid volatile losses. Recovery of spotted radioactivity was >70% in all cases. Product losses, if they did occur, would be independent of the inhibitor used. Radioactivity present in each zone was determined by LSS.

Preparation of Spinach Leaf Extracts for the Conversion of MVA to IPP

Because chloroplastic activities are lower than cytosolic activities for the enzymes that convert MVA to IPP (9), whole leaf extracts were prepared for this assay. Segments (1 cm^2) of spinach leaves were mixed with one-third of their fresh weight of PVP in 2.5 mL of homogenization medium per gram fresh weight of spinach leaves. The homogenization medium consisted of 50 mM Tris-maleate (pH 7.0), 4 mM $MgCl_2$, 2 mM $MnCl_2$, and 10 mM 2-mercaptoethanol. This suspension was ground at top speed in a Sorvall Omnimixer for 30 s at 4°C. The homogenate was squeezed through eight layers of cheesecloth, and the resulting suspension was centrifuged at 27,000*g* for 15 min. The supernatant fraction was centrifuged at 85,000*g* for 1.2 h. The supernatant from the second centrifugation was used as the source of enzyme activity.

The assay mixture (0.5 mL per assay) for measuring conversion of MVA to IPP contained 50 mM Tris-maleate (pH 7.0), 5 mM iodoacetamide, 4 mM $MgCl_2$, 2 mM $MnCl_2$, 4 mM ATP, 11 μM R-[2-^{14}C]MVA, and 100 μL of supernatant (250 μg protein mL^{-1}). Clomazone (100 μM) was tested as an inhibitor. Reactions were stopped after 30 min at 25°C by the addition of 0.5 mL of acetone. As determined in separate assays, iodoacetamide inhibited IPP isomerase (17) and hence the conversion of IPP to dimethylallyl pyrophosphate and subsequent higher molecular weight products.

After the reaction was stopped, the acetone was removed under a stream of N_2, and 30 μL of the reaction mixture was applied to a 3- × 46-cm Whatman No. 2 paper strip. The chromatogram was developed by descending chromatography in a solvent system composed of 1-butanol:HCOOH:water (77:10:13, v/v/v) (5). In this system MVA, MVAP, MVAPP, and IPP had R_F values of 0.76 to 0.86, 0.36 to 0.40, 0.01 to 0.10, and 0.12 to 0.20, respectively. After development, the paper strip was air dried, and a series of 1-cm-wide strips were cut across each chromatogram and added to scintillation vials; radioactivity was measured by LSS.

Clomazone Metabolism in Greening Seedlings

Equal weights of soybean (four seeds) and velvetleaf (60 seeds) seeds were placed in Petri dishes lined with germination paper containing 8 mL of H_2O and 0.2 μCi of [^{14}C]methyleneclomazone to give a final clomazone concentration of 10 μM. Plates were placed in the dark at a 30° angle. After 2 d, the plates were transferred to a lighted growth chamber (20) for an additional 2 d. Individual plates were removed at 2, 3, and 4 d, and plants were harvested; ^{14}C was extracted from the entire seedlings (cotyledons and radicles). Procedures for tissue extraction with 95% (v/v) methanol and chromatographic analysis via HPLC of extracted ^{14}C-compounds have been previously described (19, 20).

RESULTS

Effect of Clomazone on Pigment Levels

Clomazone decreased both Chl and carotenoid contents of barley, spinach, velvetleaf, and soybean (Table I); however, the relative sensitivity of the species differed. The order of sensitivity from greatest to least, as determined by carotenoid and Chl levels, was velvetleaf, spinach, barley, and soybean. These results are consistent with those obtained in earlier studies with soybean and velvetleaf seedlings that demonstrated that velvetleaf shoot fresh weight reduction was 162 times more sensitive to clomazone than was soybean (20). In addition, these results show that spinach was sensitive to clomazone *in vivo* and, thus, should have a sensitive target site *in vitro*.

Effect of Clomazone on IPP Incorporation

Clomazone did not affect IPP incorporation into total acid-labile products in spinach chloroplasts (Fig. 1). However, the sulfhydryl reagent iodoacetamide, a known inhibitor of IPP isomerase (17), greatly decreased the amount of IPP incorporated (Fig. 1). Product distribution among the terpenoid alcohols released after acid hydrolysis also did not differ between the control and the 100 μM clomazone treatment (Fig. 1). Again, iodoacetamide decreased the amount of IPP incorporated into each of the prenyl alcohols identified. Thus, both spinach IPP isomerase and prenyl transferase(s) in isolated chloroplasts were insensitive to the action of clomazone.

Table I. *Chl and Carotenoid Contents in Seedlings of Various Species Germinated and Grown for 7 d in Clomazone*

Species	Clomazone	Chl	Carotenoids
	μM	% of control[a]	
Barley	0	100	100
	0.1	63	59
	1.0	41	47
	10.0	15	21
	50.0	3	8
Spinach	0	100	100
	0.1	41	55
	1.0	32	38
	10.0	5	14
	50.0	2	1
Velvetleaf	0	100	100
	0.1	18	13
	1.0	3	3
	10.0	1	0
	50.0	0	0
Soybean	0	100	100
	0.1	98	102
	1.0	88	90
	10.0	76	71
	50.0	38	31
LSD (0.05)		8	13

[a] Control values for Chl in barley, spinach, velvetleaf, and soybean were 160, 190, 210, and 140 nmol g^{-1} fresh weight, respectively. Control values for carotenoids in barley, spinach, velvetleaf, and soybean were 15.8, 21.4, 18.6, and 11.4 nmol g^{-1} fresh weight, respectively.

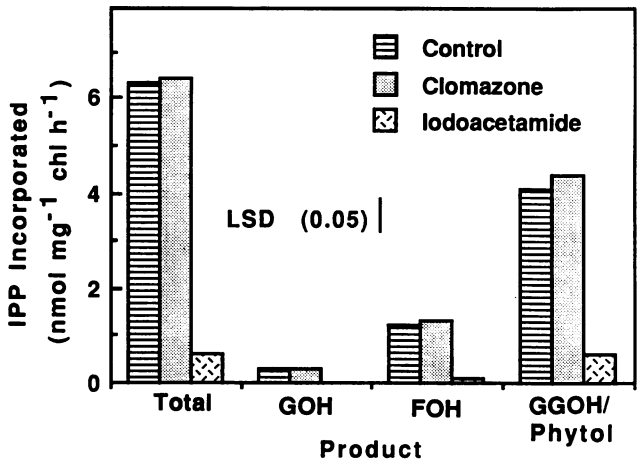

Figure 1. IPP incorporation into prenyl alcohols by isolated spinach chloroplasts in the presence of 100 μM clomazone or 100 μM iodoacetamide. GOH, geranol; FOH, farnesol; GGOH, geranylgeranol.

Effect of Clomazone on the Synthesis of IPP

Because clomazone did not inhibit the incorporation of IPP into terpenoids in isolated chloroplasts (Fig. 1), the effect of clomazone on the synthesis of IPP from MVA was addressed. Spinach leaf extracts were capable of forming IPP from MVA (Fig. 2), and 100 μM clomazone did not affect production of IPP or the intermediates MVAP and MVAPP (Fig. 2). This result is verified by the absence of an effect of clomazone on the amount of MVA present at the end of the assay (Fig. 2).

Clomazone Metabolism in Greening Seedlings

If young, greening seedlings of a particular clomazone-susceptible species do not metabolize clomazone but show clomazone injury, bioactivation of clomazone to a phytotoxic chemical could be ruled out in that species. However, both greening soybean and velvetleaf seedlings metabolized clomazone (Fig. 3). Although greening seedlings of both species metabolized clomazone at about the same rate, metabolism was slower than that observed with older seedlings (20) and cells (19) in which metabolite concentrations were higher than clomazone concentrations 72 h after clomazone treatment. Compared with soybean seedlings, velvetleaf seedlings contained slightly higher concentrations of clomazone at 2 and 3 d. However, these differences in clomazone concentration were not of sufficient magnitude to explain the differences in susceptibility of soybean and velvetleaf to clomazone (162-fold). Furthermore, even though soybean and velvetleaf seedlings contained equal concentrations of clomazone at 4 d (Fig. 3), velvetleaf was noticeably injured, whereas soybean had no visible symptoms.

Soybean and velvetleaf seedlings produced the same five major clomazone metabolites based on HPLC retention times (Fig. 4). Differences did exist for the distribution of metabolites between soybean and velvetleaf at 2 d (Table II). However, by 4 d, there were only minor differences in the metabolite distribution profiles between soybean and velvetleaf (Table II). Thus, for these two species the magnitude of

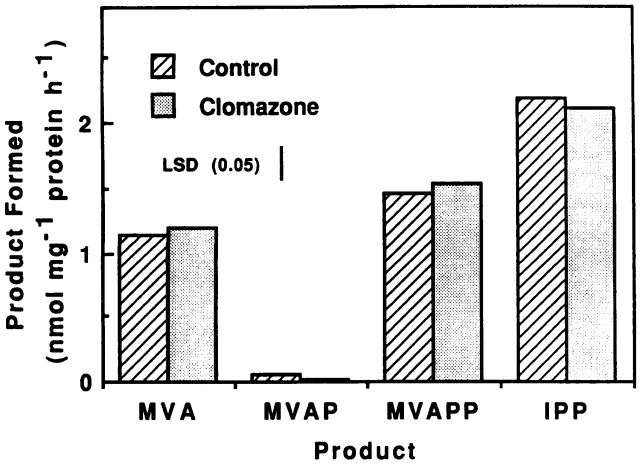

Figure 2. MVAP, MVAPP, and IPP production from MVA by spinach leaf extracts in the presence of 100 μM clomazone.

qualitative and quantitative differences in clomazone metabolites is insufficient to explain their relative susceptibility to clomazone.

DISCUSSION

Published experimental results support the hypothesis that clomazone interferes with the early stages of terpenoid biosynthesis in plants. First, consistent with our results (Table I), other clomazone-susceptible species show decreased levels of plastid pigments when exposed to the herbicide (6). Second, the phytylation of chlide is reduced in illuminated, etiolated seedlings of pitted morningglory, which could result from an inhibition of phytol synthesis (6). Third, longitudinal growth of newly formed internodes of peas is reduced by clomazone, and the reduction is reversed with exogenous applications of gibberellic acid, indicating that GA_3 synthesis may be inhibited (15). Fourth, the *in vitro* formation of phytoene, phytol, and kaurene from MVA are reportedly inhibited by clomazone (16). As a result of these findings, the enzymes in the terpenoid pathway from IPP to prenyl phosphates were thought to be sensitive to clomazone. More specifically, clomazone inhibition of IPP isomerase and/or prenyl transferase(s) was thought to be responsible for *in vitro* inhibition of terpenoid synthesis by clomazone (16). However, we have found no direct inhibition of IPP isomerase or prenyl transferase in isolated spinach chloroplasts (Fig. 1). Our results are similar to those reported recently with daffodil chromoplasts and mustard seedling etioplasts, in which clomazone did not affect the *in vitro* activities of the plastid enzymes catalyzing the steps from IPP to phytoene (12). In addition, no effect of clomazone was found on the extractable activities of the enzymes leading from IPP to phytoene when mustard seedlings were grown in the presence of clomazone (12). Thus, clomazone does not appear to directly affect the enzymes from IPP to phytoene, contradicting previous reports by Sandmann and Boger (16).

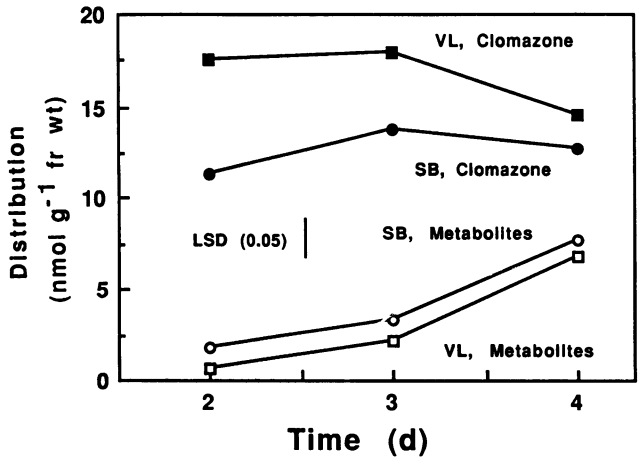

Figure 3. Time courses of clomazone and clomazone metabolite accumulation in soybean (SB) and velvetleaf (VL) seedlings germinated in and grown 4 d in 10 μM [^{14}C]clomazone.

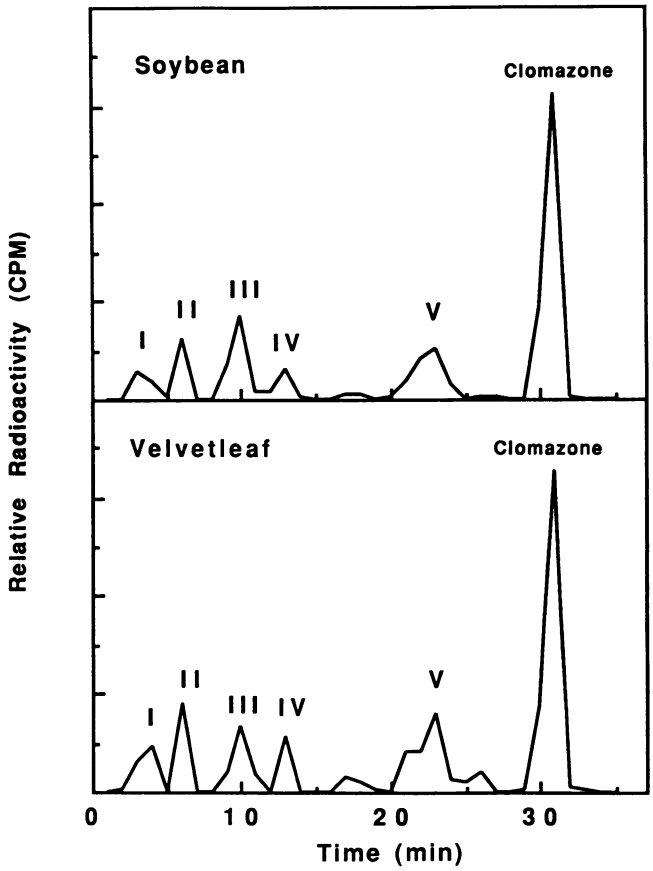

Figure 4. HPLC elution profiles of [^{14}C]compounds extracted from soybean and velvetleaf greening seedlings after exposure to 10 μM [^{14}C]clomazone for 4 d.

Clomazone inhibition of IPP production, instead of IPP utilization, might explain the *in vivo* effects of clomazone. MVA, the immediate terpenoid precursor of IPP, is formed from HMG-CoA, and this reaction is catalyzed by the enzyme, HMG-CoA reductase (EC 1.1.1.34) (2). Three enzymes are involved in the conversion of MVA to IPP. These enzymes produce MVAP, MVAPP, and IPP (2). MVAPP decarboxyl-

Table II. *Quantitation of Peaks from Figure 4*

Values given are concentrations of total metabolites and individual peaks as a percentage of total metabolites

Time	Species	Total Metabolites	Product				
			I	II	III	IV	V
d		*nmol g⁻¹ fresh wt*	*% of total metabolites*				
2	Soybean	2.0	18.4	20.4	9.2	5.9	30.3
2	Velvetleaf	0.9 [a]	2.3 [a]	9.1 [a]	29.5 [a]	2.3 NS	40.9 [a]
3	Soybean	2.7	18.7	17.5	7.8	6.0	31.9
3	Velvetleaf	2.0 [a]	10.6 [a]	15.5 NS	22.3 [a]	10.7 [a]	25.2 NS
4	Soybean	6.8	11.5	17.0	19.1	10.9	28.8
4	Velvetleaf	6.1 NS	15.0 NS	21.7 NS	14.3 [a]	14.0 NS	29.0 NS

[a] Significant difference at 0.05; *t* test.

ase (EC 4.1.1.33) has been shown to be the rate-limiting step among these three enzymes and is inhibited by phenolic acids (10). However, clomazone showed no effect on the production of IPP from MVA (Fig. 2), indicating no inhibition of any of the MVA-metabolizing enzymes.

HMG-CoA reductase, the rate-limiting step in the cholesterol biosynthetic pathway in animals, plays an important role in the regulation of cholesterol biogenesis (3). Inhibition of plant HMG-CoA reductase would result in the lack of synthesis of pigments as observed with clomazone. However, in a direct assay for the effect of clomazone on HMG-CoA reductase, no *in vitro* inhibition was observed (22).

Using the basal region of barley leaves that incorporate $^{14}CO_2$ into carotenoids (8), we have shown that clomazone had no direct effect on carotenoid synthesis from $^{14}CO_2$ after 1 h (unpublished data). Although no direct effect of clomazone on terpenoid synthesis was observed, clomazone may inhibit chloroplast biogenesis and thus indirectly affect Chl and carotenoid synthesis. Furthermore, regulation of the terpenoid synthesis pathway is complex (7), and thus, many possibilities exist for indirect effects of clomazone on this pathway. Clomazone may interfere with this regulation by some unknown mechanism, resulting in lack of terpenoid synthesis *in vivo*.

Clomazone bioactivation may explain the absence of a direct effect of clomazone on the terpenoid pathway when assayed *in vitro*. Because clomazone can be metabolized by sensitive species (14, 18–21) and young greening seedlings (Fig. 3), a clomazone metabolite may be the active agent causing the observed *in vivo* effects. Clomazone metabolites from clomazone-sensitive cotton cells were active against velvetleaf seedlings (14). However, their activity was less than that produced by equal concentrations of clomazone. On the other hand, other reports dealing with clomazone metabolism have failed to demonstrate selective bioactivation of clomazone (as determined by production of a unique metabolite) by sensitive species (18–21). We found greening seedlings of soybean and velvetleaf to produce similar amounts of the same clomazone metabolites (Fig. 4). Because the identity of all the clomazone metabolites has not yet been elucidated or their biological activity tested, bioactivation remains as a possible explanation for clomazone selectivity and for the absence of a direct effect of clomazone on terpenoid synthesis.

LITERATURE CITED

1. **Arnon DI** (1949) Copper enzymes in isolated chloroplasts: polyphenoloxidase in *Beta vulgaris*. Plant Physiol **24:** 1–15
2. **Bach TJ** (1987) Synthesis and metabolism of mevalonic acid in plants. Plant Physiol Biochem **25:** 163–178
3. **Bach TJ** (1988) Current trends in the development of sterol biosynthesis inhibitors: early aspects of the pathway. J Am Chem Soc **65:** 591–595
4. **Block MA, Joyard J, Douce J** (1980) Site of synthesis of geranylgeraniol derivatives in intact spinach chloroplasts. Biochim Biophys Acta **631:** 210–219
5. **Dugan RE, Rasson ER, Porter JW** (1968) Separation of water-soluble steroid and carotenoid precursors by DEAE-cellulose column chromatography. Anal Biochem **22:** 249–259
6. **Duke SO, Kenyon WH, Paul RN** (1985) FMC 57020 effects on chloroplast development in pitted morning glory (*Ipomoea lacunosa*) cotyledons. Weed Sci **33:** 786–794
7. **Gray JC** (1987) Control of isoprenoid biosynthesis in higher plants. Adv Bot Res **14:** 25–91
8. **Heintze A, Gorlach J, Leuschner C, Hoppe P, Hagelstein P, Schutze-Siebert D, Schultz G** (1990) Plastidic isoprenoid synthesis during chloroplast development: change from metabolic to a division-of-labor stage. Plant Physiol **93:** 1121–1127
9. **Kreuz K, Kleinig H** (1981) On the compartmentation of isopentenyl diphosphate synthesis and utilization in plant cells. Planta **153:** 578–581
10. **Lalitha R, George R, Ramasarma T** (1989) Mevalonate metabolizing enzymes in *Arachis hypogea*. Mol Cell Biochem **87:** 161–170
11. **Lichtenthaler HK** (1987) Chlorophylls and carotenoids: pigments of photosynthetic biomembranes. Methods Enzymol **148:** 350–382
12. **Lutzow M, Beyer P, Kleinig H** (1990) The herbicide Command does not inhibit the prenyl diphosphate-forming enzymes in plastids. Z Naturforsch **45C:** 856–858
13. **Mullet JE, Chua NH** (1983) *In-vitro* reconstitution of synthesis, uptake and assembly of cytoplasmically synthesized chloroplast proteins. Methods Enzymol **97:** 502–509

14. **Norman MA, Liebl RA, Widholm JM** (1990) Uptake and metabolism of clomazone in tolerant-soybean and susceptible-cotton photomixotrophic cell suspension cultures. Plant Physiol **92:** 777–784
15. **Sandmann G, Boger P** (1986) Interference of dimethazone with formation of terpenoid compounds. Z Naturforsch **41C:** 729–732
16. **Sandmann G, Boger P** (1987) Interconversion of prenyl pyrophosphates and subsequent reactions in the presence of FMC 57020. Z Naturforsch **42C:** 803–807
17. **Spurgeon SL, Sathyamoorthy N, Porter JW** (1984) Isopentenyl pyrophosphate isomerase and prenyltransferase from tomato fruit plastids. Arch Biochem Biophys **230:** 446–454
18. **Vencill WK, Hatzios KK, Wilson HP** (1990) Absorption, translocation, and metabolism of ^{14}C-clomazone in soybean (*Glycine max*) and three *Amaranthus* weed species. J Plant Growth Regul **9:** 127–132
19. **Weimer MR, Balke NE, Buhler DD** (1992) Absorption and metabolism of clomazone by suspension-cultured cells of soybean and velvetleaf. Pest Biochem Physiol **42:** 43–53
20. **Weimer MR, Buhler DD, Balke NE** (1991) Clomazone selectivity: absence of differential uptake, translocation, or detoxication. Weed Sci **39:** 529–534
21. **Weston LA, Barrett M** (1989) Tolerance of tomato (*Lycopersicon esculentum*) and bell pepper (*Capsicum annum*) to clomazone. Weed Sci **37:** 285–289
22. **Won J, Hatzios KK** (1991) Stimulation of corn HMG-CoA reductase activity by bleaching herbicides. Weed Sci Soc Am Abstr **31:** 59