Effects of the Insecticide Phosmet on Solitary Bee Foraging and Nesting in Orchards of Capitol Reef National Park, Utah

DIANE G. ALSTON,[1,2] VINCENT J. TEPEDINO,[1,3] BROSI A. BRADLEY,[4] TRENT R. TOLER,[5] TERRY L. GRISWOLD,[1,3] AND SUSANNA M. MESSINGER[6]

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ABSTRACT Capitol Reef National Park, in southcentral Utah, contains 22 small orchards planted with antique fruit varieties by Mormon pioneers beginning over a century ago. The orchards continue to be managed in a pick-and-pay program, which includes spraying with phosmet to suppress codling moth (*Cydia pomonella* L.). The park is also home to a rich diversity of flowering plants, many of which are rare, bee-pollinated, and have populations within 1 km of the orchards. Over 3 yr, we studied the short-term effects of phosmet spraying on bee populations: (1) foraging on plants within the orchard understory and adjacent to it; and (2) nesting in, and at several distances from, the orchards. We recorded a rich bee fauna (47 taxa) in the orchards and on plants nearby. In 2 yr (2002 and 2004), we found no difference in the number of native bee visits to several species of plants flowering in and near to orchards immediately before and 1 d after spraying. Conversely, our nesting studies using the semidomesticated alfalfa leafcutting bee, *Megachile rotundata* (F.), showed strong significant declines in the number of adult males, nesting females, and progeny production subsequent to spraying at distances up to 160 m from sprayed orchards where the bees were presumably foraging. We showed that *M. rotundata* is negatively affected by phosmet spraying and suggest that caution should be exercised in its use in areas where bees are apt to forage.

KEY WORDS conservation, lethal effects, *Megachile*, pollination, solitary bees

The judicious use of insecticides and other means to control insect pests is nowhere more important than in areas where preservation of native biodiversity is paramount. U.S. National Parks are challenged with a mission to preserve biodiversity in its parks while managing pests that threaten native and introduced flora. An example is Capitol Reef National Park, where 22 small (0.2–3.2 ha) working orchards containing antique varieties of nine fruit tree crops are protected as a Rural Historic Landscape (Gilbert and McKoy 1997). These varieties are deemed worthy of preservation because of their antique germplasm and because they represent an aspect of the agricultural history of the western United States. The orchards were originally planted by Mormon settlers in the small community of Fruita, UT, beginning in 1880. The fruits are currently harvested and sold through a pick-and-pay program.

Among the harvested crops are apple (*Malus pumila* Mill.) and pear (*Pyrus communis* L.), both of which are attacked by codling moth, *Cydia pomonella* L. (Lepidoptera: Tortricidae), an invasive and economically injurious insect. If the pick-and-pay program is to continue as a viable agricultural operation, codling moth must be managed; the insecticide of choice is phosmet, a contact organophosphate with a broad spectrum of activity (Brunner and Smith 1993, Brunner et al. 2004).

Among the potential victims of phosmet are bees. Native solitary bees are particularly important in Capitol Reef National Park because of their role as pollinators of the richly diverse flora. The park encompasses a large number of rare plant species (Heil et al. 1993); nine species are listed under the U.S. Endangered Species Act as threatened or endangered, and >30 others are listed as sensitive. All listed plant species, and an unknown percentage of those less rare, depend on insect pollinators to mediate seed production (Tepedino 2000; unpublished data). Five of the rare species have populations within 0.7 km of the orchards and may be adversely affected if phosmet spraying reduces the number of pollinator visits to their flowers.

Phosmet is listed by the U.S. Environmental Protection Agency as highly toxic to bees (U.S. EPA 2000). However, this rating is because of topical application tests on three species, two of which are introduced: the honey bee (*Apis mellifera* L. and alfalfa leafcutting bee [*Megachile rotundata* (F.)], and

[1] Department of Biology, 5305 Old Main Hill, Utah State University, Logan, UT 84322-5305.
[2] Corresponding author, e-mail: dianea@biology.usu.edu.
[3] USDA–ARS Bee Biology and Systematics Laboratory, Logan, UT 84322-5310.
[4] Box 1071, Juniata College, Huntingdon PA 16652.
[5] HDR Engineering, Salt Lake City, UT 84105.
[6] Department of Ecology and Evolutionary Biology, 1300 Kraus Natural Sciences Building, University of Michigan, Ann Arbor, MI 48109-1048.

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one which is native, the alkali bee (*Nomia melanderi* Cockerell) (Johansen et al. 1983, Johansen and Mayer 1990). Such tests are not necessarily indicative of field applications. The only field study of the effects of phosmet on bees of which we are aware (Johansen et al. 1983) did not find differences in susceptibility among the three bee species. Nevertheless, it is well known that these bee species may differ greatly from each other in their susceptibility to specific insecticides (Johansen et al. 1983), and it is to be expected that they will also differ from native solitary bee species in their respective abilities to withstand phosmet.

This study addresses the short-term effects of phosmet application on foraging and nesting behavior of solitary bees in Capitol Reef National Park. Specifically, we quantify the effects of phosmet on flower visitation, mortality, and brood production by bees in and near antique orchards.

Materials and Methods

Study Site. Experiments were conducted within and adjacent to two orchards ≈1.5 km apart in Fruita, UT: Jackson (1.1 ha, mixture of primarily apple and pear) and Krueger (1.9 ha, mixture of primarily apple and peach [*Prunus persica* L. Batsch.]). Phosmet (Imidan 70-W at 4.5 kg/ha; Gowan Co., Yuma, AZ) was applied to apple and pear trees with an orchard air blast sprayer (3,743 liters of dilute solution/ha) on 23 May, 11 June, and 1 July in 2002; on 22 May, 10 June, and 1 July in 2003; and on 18 May and 21 June in 2004 to suppress populations of codling moth. Two additional orchards served as unsprayed controls for the bee nesting experiments: Clarke (1.0 ha of sweet cherry [*Prunus avium* L.]; 0.3 and 1.2 km from Jackson and Krueger orchards, respectively) and Carrell (0.7 ha of peach; 1.2, 1.3, and 1.6 km from Clarke, Jackson, and Krueger orchards, respectively).

Flower Visitation. Insect visitation to flowers was measured on plants in abundant bloom either within or immediately adjacent to Jackson and Krueger orchards. To minimize the effects of background mortality, visitation was estimated as close to phosmet applications as feasible, i.e., 1 d before and 1 d after on all three application dates in 2002 and on 21 June in 2004. Flowering plants were ≈10 or 50 m from the nearest sprayed trees in the Jackson and Krueger orchards, respectively. In 2002, plant species sampled were *Aster foliaceus* Lindl. (Asteraceae), *Asclepias speciosa* Torr. (Asclepiadaceae), *Convolvulus arvensis* L. (Convolvulaceae), *Grindelia squarrosa* (Pursh) Dunal. (Asteraceae), *Gaillardia spatulata* Gray (Asteraceae), *Melilotus officinalis* L. Pallas (Fabaceae), *Medicago sativa* L. (Fabaceae), and *Sphaeralcea coccinea* (Nutt.) Rydb. (Malvaceae). In 2004, only *A. speciosa, M. officinalis,* and *M. sativa* were sampled.

Mixed-species patches of open flowers were monitored for 30 min each in the morning (between 0945 and 1145 hours) and afternoon (between 1330 and 1530 hours) at each orchard site as a single observer walked among the patches. Counts were made of every flower visit, including "new" visitors as well as those making multiple visits, and thus are an estimate of total insect visitation. Insect visitors were identified by sight to the lowest taxonomic level possible without disturbance. To verify and improve pollinator identifications, representative specimens were collected during 30-min bouts at the conclusion of each visitation observation period in 2002. Inclement weather on 24 May and 2 July 2002 caused postponement of insect collections for 1 d. In 2004, because of previous experience, we had greater familiarity with the pollinator taxa and opted to eliminate collections to minimize the potential effect of insect removal on the results. Ambient temperature was measured with a digital thermometer in each orchard during foraging observation periods in both years. Cloud cover and wind speed measurements were obtained in 2004 only from the Park Visitor Center 0.6–2.0 km away from Jackson and Krueger orchards, respectively. Cloud and wind data were not available from the Park Service in 2002.

Nesting of Solitary Bees. In 2003, we examined the effects of phosmet on a representative solitary bee, the alfalfa leafcutting bee (*Megachile rotundata*), whose nests were moved into orchards <24 h after spraying. *M. rotundata* is an introduced, but widespread, species managed as a commercial alfalfa pollinator (Richards 1984), and had been previously reported from the park. On 19 June, we placed bees (≈300 female and 700 male pupae in open petri dishes to allow emergence) and four wooden nesting blocks (40 by 20 by 8 cm) within a shelter (0.6 m^2) mounted on a wooden post (1.5–2.0 m height) in the center of each of two orchards that would not be sprayed with phosmet (Carrell and Clarke orchards). Each nesting block contained ≈150 6-mm-diameter tunnels filled with paper soda straws. We confirmed that at least 25 female bees were actively nesting before phosmet was applied to the nearby Krueger and Jackson orchards on 1 July. On 1 July, we estimated the size of the bee population nesting in each block in Carrell and Clarke orchards by counting the number of straws with females inside after dark with the aid of a flashlight. At 0600 hours on 2 July, before bees became active, we divided the total number of nesting females in each Carrell and Clarke orchard into two approximately equal groups and moved them in their paper straw nests to nesting blocks in either one of the phosmet-treated orchards or to the other unsprayed orchard (i.e., one half of the bees in Clarke were moved to the sprayed Krueger and one half to the unsprayed Carrell orchard; one half the bees in Carrell were moved to sprayed Jackson and one half to unsprayed Clarke orchard). This design was used to remove bias by subjecting all bees to a movement treatment. The legume understory of all orchards was in full bloom with either *M. sativa* or *M. officinalis.* We subsequently monitored nesting blocks and recorded the activity of bees in each of the four orchards every 4–5 d from 2 July to 1 August.

In 2004, we tested for effects of phosmet residues on survival and nesting of *M. rotundata* when nests were placed at three distances from sprayed orchards (10, 100, and 160 m). We placed ≈250 female and 500 male

Table 1. Numbers of bees foraging on flowers of understory plants in two orchards 1 d before and 1 d after (separated by dashes) application of the insecticide phosmet

Year and orchard	Observation period	AF	AS	CA	GSP	GSQ	MO	MS	SC
2002[a]									
Jackson	am	71–41[b]	89–118	—[c]	23–7	2–0	—	16–21/18–35	—
	pm	90–29	89–61	—	15–35	70–11	—	19–17/29–7	—
Krueger	am	—	77–114	17–0	—	73–152	1–118	36–5	83–17
	pm	—	7–115	0–0	—	137–171	87–203	20–38	139–227
2004[d]									
Jackson	am	—	—	—	—	—	21–0	22–0	—
	pm	—	—	—	—	—	45–5	18–3	—
Krueger	am	—	109–64	—	—	—	—	4–30	—
	pm	—	74–60	—	—	—	—	7–10	—

Thirty-minute observations were conducted in each the morning (am) and afternoon (pm) on blooming plant species in Jackson and Krueger orchards in 2002 and 2004.

[a] In 2002, plant species were sampled on 22 and 24 May (*G. spatulata, M. sativa,* and *S. coccinea*), 10 and 12 June (*A. speciosa, M. officinalis,* and *M. sativa*), and 30 June and 2 July (*A. foliaceus, C. arvensis,* and *G. squarrosa*).

[b] Numbers in couplets (x-y) represent pollinator counts from 1 d before (x) and 1 d after (y) insecticide applications. Counts on MO were made on two separate dates in the Jackson orchard in 2002 and are separated by a slash.

[c] — indicates designated plant was not present in the designated orchard.

[d] In 2004, all plant species were sampled on 20 and 22 June.

AF, *Aster foliaceus;* AS, *Asclepias speciosa;* CA, *Convulvulus arvensis;* GSP, *Gaillardia spatulata;* GSQ, *Grindelia squarrosa;* MO, *Melilotus officinalis;* MS, *Medicago sativa;* SC, *Sphaeralcea coccinea.*

M. rotundata pupae and three nesting blocks (same materials and dimensions as described for 2003) in each of four locations with blooming alfalfa on 27 May: 10 and 100 m from the Jackson orchard and 100 and 160 m from the Krueger orchard. First indication of bees nesting in blocks was noted on 1 June. We were unable to include additional untreated orchards in our test because no others had adequate patches of blooming alfalfa to sustain nesting of the leafcutting bee.

On 20 June (1 d before phosmet applications), 23 June (2 d after), and 1 August (41 d after), nesting blocks were surveyed between 2030 and 2230 hours after bees had returned to their nests to assess nesting activity and cell production. We recorded the status of all nests in each block by removing straws, holding them to a bright light and recording the contents: empty, partially filled, or completely filled and capped. Straws only partially filled with cells and progeny were marked on the exterior at the outermost point of nesting activity to monitor future growth. We also counted the number of male and female *M. rotundata* bees in empty or partially filled holes.

In 2003, we also conducted two other experiments to coincide with the 22 May and 10 June phosmet spray dates; however, these were unsuccessful. We used *Osmia lignaria* Say, a native mason bee that is commercially managed as an orchard crop pollinator (Bosch and Kemp 2001), and *M. rotundata* for the two experiments, respectively (≈50 female and 100 male pupae and requisite nesting material were used for each experiment), but few females established nests. These experiments were terminated.

Data Analyses. The nonparametric statistic, Wilcoxon signed rank test (Analytical Software 2000) was used to compare the number of foraging bees on flower patches between before and after spray observations. Bee visitation counts were regressed against mean ambient temperature across sampling dates for each orchard in each year (SAS Institute 2003). Frequency of completed nest tunnels and nesting adults were compared between pre- and post-spray dates for sprayed and unsprayed orchards (2003) and for nests at the three distances from sprayed orchards (2004) with χ^2 analyses (SAS Institute 2003).

Results

Flower Visitors. We present only data for bees because they constituted the overwhelming majority of flower visitors; wasps, butterflies, and flies were few (syrphids, abundant in 2003, were uncommon in 2002 and 2004). We observed and collected 47 bee taxa in 22 genera on the flowers of the eight blooming plant species in, or near to, the two orchards over 2 yr (a complete list with plant associations by year is available from the corresponding author). Many more taxa were distinguished in 2002, when bees were both collected and observed, than in 2004, when we only observed (43 species in 2002; 9 in 2004, identified mostly to genus). With two exceptions (*A. mellifera,* the honey bee, and *M. rotundata,* the alfalfa leafcutting bee), all species are native to North America. The leafcutting/mason bee family Megachilidae was represented by the largest number of species (≥19). Only 15 of the 47 species were documented from both orchards.

Bee Foraging. Phosmet applications to nonblooming fruit trees had no significant effect on abundance of bees foraging on flowers of groundcover plants in, or near to, orchards (Table 1). The number of foragers 1 d after spraying was indistinguishable from those present 1 d before treatment. Seventeen of the 32 comparisons had fewer visitors after phosmet treatment than before, and 14 comparisons had more visitors after treatment (in one comparison, no pollinators were observed). When grouped by dates of observation, pairs of pre- and post-spray comparisons

Table 2. Statistics for Wilcoxon signed rank test comparing pairs of pre- and post-spray bee visitation counts on flowers of ground cover plants from four observation periods

Year	Observation dates	Median (and first quartile) values	
		Prespray	Postspray
2002	22 and 24 May	21.5 (16.8)	19.0 (9.5)
	10 and 12 June	53.0 (9.8)	114.5 (41.5)
	30 June and 2 July	70.5 (5.8)	20.0 (0)
2004	20 and 22 June	21.5 (9.8)	7.5 (0.8)

were all nonsignificant (Wilcoxon signed rank test, $P > 0.05$; Table 2).

Our pre- and post-spray comparisons of flower visitation were not influenced by weather. We found no relationship between temperature (both years) or cloud cover and wind (2004 only) and bee foraging activity. Regressions of bee counts against mean ambient temperatures during observation periods across sampling dates within orchards were not significant for any comparison (for Jackson orchard: $r^2 = 0.001$, df = 23, $P = 0.88$; for Krueger orchard: $r^2 = 0.006$, df = 23, $P = 0.71$).

Nesting of Solitary Bees. In 2003, we found a significant reduction in the number of *M. rotundata* bees nesting within orchards after applying phosmet compared with bees nesting in unsprayed orchards ($\chi^2 = 188.3$, df = 3, $P < 0.001$; Table 3). When the contingency table was partitioned into its three degrees of freedom, the only significant difference in the number of nests completed after the movement of nesting blocks was between sprayed and unsprayed orchards ($\chi^2 = 185.6$, df = 1, $P < 0.001$). There was no difference between the two orchards sprayed after moving nesting blocks ($\chi^2 = 1.7$, df = 1, $P > 0.05$) or between the two unsprayed orchards ($\chi^2 = 1.1$, df = 1, $P > 0.05$).

In 2004, we observed a precipitous decline in the number of nesting bees from before to after spraying ($\chi^2 = 678.1$, df = 3, $P < 0.0001$), and this reduction was significant at each of the three distances ($P < 0.001$; Table 4). Male counts were low, so we combined males and females for comparisons. The percentage decline in adult bees was 72.5% for males and 88.5% for females across all sites.

As might be expected with such a precipitous decline in the number of nesting females after spraying, nest production also declined significantly. The numbers of empty and partial nests showed modest declines from 20 June to 1 August (overall, −3.4 and −4.1%, respectively) indicating that very few new nests were produced after phosmet was applied. Indeed, the number of completed nests rose by only 10.0% during the same period (Table 4). Roughly one half of these were completions of nests that had been partially filled before spraying. There was also a bias in the distribution of completions: most completed nests were at the Krueger 100-m site (69.8% of total nests completed after spraying); Krueger also had the highest percent of surviving females. Thus, there was no clearcut effect of nest distance on numbers of surviving females or nest completions.

Table 3. Number of nests made by female *M. rotundata* in 2003 before (19 June to 1 July) and after (2 July to 1 Aug.) they were moved from an unsprayed orchard (Carrell or Clarke) to either a phosmet-treated orchard (Jackson or Krueger) or another unsprayed orchard on the morning after spraying

Nest location transitions by orchard	Number of nests completed	
	Before	After
Carrell-Clarke (unsprayed-unsprayed)	31	100
Clarke-Carrell (unsprayed-unsprayed)	42	190
Carrell-Jackson (unsprayed-sprayed)	67	5
Clarke-Krueger (unsprayed-sprayed)	45	10

Discussion

In a spatially and temporally circumscribed series of collections within and near two orchards, we identified 47 species of bees in 22 genera foraging on flowering plants. Unlike studies of the effects of aerial spraying of fenitrothion in northeastern Canada (review in Kevan and Plowright 1989), members of this diverse pollinator complex did not seem to be adversely affected by focused postbloom spraying of apple and pear trees with phosmet. Pre- and post-spray counts of bees visiting flowers of eight plant species in two orchards in 2 yr failed to show consistent declines in foragers after spraying. In a concurrent study of five insect-pollinated, rare plant species, we found no effect of phosmet spraying on the number of bee visits to the flowers or on seed set in plant occurrences near to (0.5–1.4 km) and far from (≥5 km) orchards (unpublished data). Thus, two data sets give little reason to curtail the phosmet spraying program as presently conducted.

Our results using nesting *M. rotundata* bees present a different picture. With this representative solitary bee, we consistently found increased mortality of adults and decreased nesting activity within and nearby phosmet-treated orchards. Significant reductions in number of *M. rotundata* males and females were observed soon after spraying at nesting blocks in the center of orchards and at distances of 10, 100, and 160 m from treated orchards, but not at nesting blocks 250 m away. In addition, cell and progeny production all but ceased at nests within 160 m of sprayed orchards but was unaffected at distances ≥250 m. Johansen et al. (1983) also reported that a sudden loss of nesting alfalfa leafcutting bees was a sign of pesticide poisoning.

How can we account for these differences? We suspect that several factors, including species-specific vulnerability, size, behavior, and age, have intertwined to yield this result. It is known that there is great variation in vulnerability to insecticides among the few bee species that have been used for comparative studies and that vulnerability changes with the insecticide (Johansen et al. 1983). Thus, it may be that *M. rotundata* is more vulnerable to phosmet than are most native bees that we recorded. Unfortunately, the

Table 4. Influence of nest distance (10, 100, and 160 m) on sensitivity of *M. rotundata* adults and nest production to phosmet application on 21 June 2004 in Jackson and Krueger orchards

Orchard	Nest distance	No. females		No. males		No. empty nests		No. partial nests		No. capped nests	
		Before[a]	After[b]	Before	After	Before	After	Before	After	Before	After
Jackson	10 m	82	1	5	0	234	230	143	146	115	116
	100 m	68	4	8	0	257	243	121	127	114	122
Krueger	100 m	177	35	12	8	115	107	175	146	202	239
	160 m	73	6	15	3	226	224	168	163	98	105
Total		400	46	40	11	832	804	607	582	529	582

[a] Bees were placed in orchards on 27 May and before-spray counts were made on 20 June.
[b] After-spray adult counts were made on 23 June, and nest production counts were made on 1 Aug.

only native bee commonly included in insecticide tests is *N. melanderi,* a species not present during our studies. Johansen et al. (1983) were unable to distinguish between *M. rotundata* and *N. melanderi* in sensitivity to phosmet. However, as a general rule, *M. rotundata* is more intolerant of insecticides than is *N. melanderi;* analysis of data from Johansen et al. (1983) showed that *M. rotundata* is more vulnerable to 23 insecticides, whereas *N. melanderi* is more vulnerable only to 3; for 23 insecticides, they showed equal sensitivities. Further analysis of the comparisons of Johansen et al. (1983) including *A. mellifera* also shows that, of the 31 insecticides (carbamates, chlorinated hydrocarbons, organophosphates) that gave different bee susceptibilities, *M. rotundata* was most susceptible of all three bee species in 26 comparisons.

Why might *M. rotundata* bees be generally more susceptible to insecticides than other species? Some of this susceptibility may be attributable to size: Johansen et al. (1983) and Johansen and Mayer (1990) suggested that *M. rotundata* was more susceptible to insecticides than the honey bee and alkali bee because of its smaller size and larger surface-to-volume ratio. Waller (1969) showed that female *M. rotundata* have increased vulnerability to some insecticides because their leafcutting habit increases the likelihood that they will contact residues. Thus, size and/or behavior may have played a role in the interspecific differences we witnessed.

Age of foraging bees may also have played a role in the different responses to phosmet of *M. rotundata* and native bees. *M. rotundata* females began nesting 2–3 wk before spray application and were at peak nest production just before and after treatments. Although some of the decline in nesting activity after phosmet sprays may have been caused by natural aging of the bee population. Tepedino and Parker (1988) found $\approx$40% of *M. rotundata* females remained alive 5 wk after emerging and foraging on alfalfa in a greenhouse. Johansen et al. (1983) reported that longevity of adult female *M. rotundata* was >6 wk. Thus, the precipitous decline we observed in post-spray mortality and progeny production was primarily caused by phosmet rather than age. Nevertheless, age may also have had an indirect effect. Johansen et al. (1983) also reported that adult bees became more susceptible to insecticides at 3 wk of age, just around the time when orchards were sprayed. Thus, *M. rotundata* may have been more vulnerable than the complex of native bees that foraged on plants in, and adjacent to, orchards. The native bees were more likely a mix of young and old and thus less likely than *M. rotundata* to show the effects of spraying.

A fourth possibility, one we can eliminate, rests on the precision that air blast insecticide application allows if carried out under calm conditions, as was done here. When application is confined to specific target trees, drift is reduced primarily to plants growing within the orchard understory: in our study, primarily alfalfa. Thus, visitors to alfalfa flowers, like *M. rotundata,* might be more likely to contact residues than bees foraging on other plant species growing both in the understory and/or adjacent to the orchards. However, this was not the case; 10 of the 32 pre- and post-spray comparisons were made on alfalfa flowers, and results were evenly split between greater numbers of visitors before and after spraying.

In conclusion, we suggest that practitioners at Capitol Reef National Park and other such sites use caution in developing insect pest management plans. We showed that phosmet is quite toxic to alfalfa leafcutting bees nesting in and near treated orchards or foraging on plants in close juxtaposition to sprayed trees; its detrimental effect on native bees in the park is undocumented. Preferable to the broad-spectrum neurotoxin, phosmet, are alternative insect controls such as insect growth regulators, microbial insecticides, and pheromone-based controls that are more specific in their effects on target lepidopteran pests (Brunner et al. 2004). Failing this, current use of degree day–based control timing methodologies and practices to reduce spray drift should be continued to minimize negative effects of insecticide sprays on native bees and the plants they service.

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