Integrative Zoology 2014; 9: 265–279 doi: 10.1111/1749-4877.12067

ORIGINAL ARTICLE

Perceived damage and areas of needed research for wildlife pests of California agriculture

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Abstract

Many wildlife species cause extensive damage to a variety of agricultural commodities in California, with estimates of damage in the hundreds of millions annually. Given the limited availability of resources to solve all human–wildlife conflicts, we should focus management efforts on issues that provide the greatest benefit to agricultural commodities in California. This survey provides quantitative data on research needs to better guide future efforts in developing more effective, practical and appropriate methods for managing these species. We found that ground squirrels, pocket gophers, birds, wild pigs, coyotes and voles were the most common agricultural wildlife pest species in California. The damage caused by these species could be quite high, but varied by agricultural commodity. For most species, common forms of damage included loss of crop production and direct death of the plant, although livestock depredation was the greatest concern for coyotes. Control methods used most frequently and those deemed most effective varied by pest species, although greater advancements in control methods were listed as a top research priority for all species. Collectively, the use of toxicants, biocontrol and trapping were the most preferred methods for control, but this varied by species. In general, integrated pest management practices were used to control wildlife pests, with a special preference for those approaches that were efficacious and quick and inexpensive to apply. This information and survey design should be useful in establishing research and management priorities for wildlife pest species in California and other similar regions.

Key words: agriculture, California, human–wildlife conflict, integrated pest management, survey

INTRODUCTION

Agriculture is an essential part of the California economy, accounting for US$37.5 billion annually (CDFA 2012). Agricultural commodities in California are extremely diverse, with over 400 commodities produced in 2010 (CDFA 2012). This high economic value combined with a broad diversity in commodities makes con-

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trolling damage caused by wildlife pests in California imperative, yet quite challenging. For example, a recent study investigating the economic damage caused by bird and rodent pests to just 22 commodities across 10 counties in California indicated a loss of US$168–504 million annually (Shwiff *et al.* 2009). This value takes into account only a portion of the agricultural production that occurs throughout California, and does not account for additional impacts such as structural damage to dams and levees (e.g. loss of structural integrity of irrigation canals caused by burrowing rodents), ecological damage (e.g. nesting failures for song birds) and disease transmission (e.g. spread of bubonic plague, hantavirus or leptospirosis by rodents). Although wildlife provide many intrinsic values and ecological functions, controlling wildlife damage is clearly warranted in many situations to reduce deleterious human–wildlife interactions.

Integrated pest management (IPM) is a concept that arose in the 1960s that incorporates the use of multiple management techniques to control a variety of pest taxa (Smith & van den Bosch 1967) and has more recently been effectively incorporated into wildlife pest control (Sterner 2008). One of the primary benefits of an IPM program includes more targeted and strategic use of pesticides to maximize efficacy while minimizing risk to non-target species (e.g. Ramsey & Wilson 2000). The threat of non-target exposure to pesticides is currently a major concern for many agricultural producers, wildlife management agencies and the general public, and will likely continue to be a prominent issue well into the future (Baldwin & Salmon 2011). That being said, perhaps the greatest selling point of an IPM program to most agricultural producers is simply the increase in efficacy associated with an IPM approach as compared to continued reliance on a single control method (Engeman & Witmer 2000; Sterner 2008). However, we are unsure how widely IPM programs are used to control wildlife damage. Information on the use of IPM programs combined with insight into ways to increase its incorporation into management programs should yield positive results both for agricultural producers as well as the agricultural landscape.

Management tools that are incorporated into an IPM program will vary depending on the pest species involved. Many wildlife species are considered major pests of agricultural commodities, including the California ground squirrel (*Otospermophilus beecheyi* Richardson, 1829), the pocket gopher (*Thomomys* spp.), the California vole (*Microtus californicus* Peale, 1848) and the coyote (*Canis latrans* Say, 1823), although specific threats to agricultural production are dependent on geography, climate and commodity prices. Greater insight into methods used to control this damage and ways to increase the efficacy of control programs are also needed. Quantifiable data on these issues would aid in the better allocation of research dollars to develop more effective control programs for pest species.

Although wildlife cause damage to many commodities, controlling these species can be quite costly. Situations may exist where it is economically more beneficial to incur some loss to wildlife rather than to implement an extensive control program (Gebhart *et al.* 2011). Unfortunately, there is often a lack of data available to assist agricultural producers in making a decision on whether to implement a management program for a particular wildlife pest, and, if so, which methods are most appropriate. Research into this area is clearly warranted to provide information to agricultural producers to better answer these questions.

Therefore, our goal was to develop a survey that would target individuals involved with assisting or regulating agricultural producers who experience wildlife damage in order to provide quantitative data on research needs to better guide future research efforts in developing more effective, practical and appropriate methods for managing these pests. More specifically, our primary objectives for this survey were as follows: (i) to ascertain which wildlife species were most frequently identified as major pests in California agriculture; (ii) to determine which wildlife species were most in need of additional research to develop more effective control methods; (iii) to estimate the economic damage caused by each of these species; (iv) to identify the most costly form of damage caused by each species; (v) to identify which methods are used most frequently and which are considered most effective for controlling these species, and if these methods differ, why; (vi) to determine areas where advancements are most needed to manage these species; (vii) to identify which control methods are most appealing to individuals involved in wildlife pest control; (viii) to determine if individuals involved in wildlife pest control in agriculture follow an IPM approach for managing these species, and if not, why; and (ix) to identify the most important attributes for wildlife pest control methods.

MATERIALS AND METHODS

We developed a 10-question electronic survey via SurveyMonkey (http://www.surveymonkey.com/) with multiple parts to some questions (see Baldwin *et al.* 2011b for survey). This survey was disbursed via email in 2010 to all California County Agricultural Commissioner offices, advisors and specialists within the University of California Cooperative Extension (UCCE), other University faculty who interact with agricultural producers, major Commodity Boards, California Department of Fish and Game (CDFG) biologists associated with managing wildlife in agricultural areas and United States Department of Agriculture–Wildlife Services supervisors in California. Our goal was to reach knowledgeable people from throughout the state to provide input on wildlife damage and damage management techniques. This survey was approved by the University of California, Davis, Institutional Review Board for human subject research (protocol number 201018437-1).

Survey design

For Objective 1, each survey participant ranked the top 3 wildlife species they felt resulted in the greatest number of complaints annually. This same approach was followed for Objective 2, although instead of the number of complaints, we were interested in the pests most in need of additional research on control methods. Because of the low number of responses anticipated for individual bird species (European starling, *Sturnus vulgaris* Linnaeus, 1758; American crow, *Corvus brachyrhynchos* Brehm, 1822; red-winged blackbird, *Agelaius phoeniceus* Linnaeus, 1766; tricolored blackbird, *Agelaius tricolor* Audubon, 1837; yellow-headed blackbird, *Xanthocephalus xanthocephalus* Bonaparte, 1827; Brewer's blackbird, *Euphagus cyanocephalus* Wagler, 1829; house finch, *Carpodacus mexicanus* Müller, 1776; horned lark, *Eremophila alpestris* Linnaeus, 1758; common raven, *Corvus corax* Linnaeus, 1758; black-billed magpie, *Pica hudsonia* Sabine, 1823; and yellow-billed magpie, *Pica nuttalli* Audubon, 1837), along with the relative similarity in control methods for these species, we combined them all into a single bird category for analysis. We anticipated minimal responses to some of the species provided. Therefore, if <5% of the respondents ranked a particular pest, this species was removed from further analysis.

For Objective 3, respondents were asked to evaluate the amount of damage caused by each of their 3 selected pests for 1 of 9 commodities (nut crops, tree fruit, berries, grapes, vegetable and row crops, alfalfa, rangelands, dairy and feedlots and other). Response options included 'no damage', 'slight damage (<5% reduction in profit)', 'moderate damage (5%–15% reduction in profit)', 'heavy damage (>15% reduction in profit)' and 'I don't know'. Respondents were encouraged to select 'I don't know' if they had no experience with a particular commodity group. For analysis, 'no damage' through 'heavy damage' received a score of 1–4. For descriptive purposes, we also converted these scores to estimate losses in profit using the following conversion: no damage = 0%; slight damage = 2.5%; moderate damage = 10%; and heavy damage = 20%.

Objective 4 focused on the most costly form of damage caused by wildlife pests. Possible responses included: (1) loss of crop production through direct consumption of fruit, nut, seed or vegetation; (2) loss of vigor or direct death of the plant; (3) loss of irrigation water down burrow systems; (4) damage to irrigation infrastructure; (5) consumption or contamination of feed in dairies and feedlots; (6) transmission of disease to crop or livestock; (7) depredation of livestock; and (8) other. Due to a low number of responses for options 3 (n = 5) and 6 (n = 5), as well as a similarity in these forms of damage, options 3–4 and 5–6 were combined for analysis.

For Objective 5, we were interested in the frequency and effectiveness of control methods used to manage wildlife pests. Potential options included: (1) toxicants; (2) burrow fumigants; (3) traps; (4) habitat modification/cultural practices; (5) biocontrol (i.e. increasing natural predation); (6) physical exclusionary devices; (7) chemical repellents; (8) frightening devices (e.g. propane cannons and electronic distress calls); (9) gas explosive devices (devices that explode tunnel systems [e.g. Rodenator, Emmett, ID, USA]); (10) shooting; and (11) other methods. We were also interested in the survey participant's opinion as to why the most frequently used and most effective methods might differ. Potential responses included: (1) the methods did not differ; (2) the most effective method was too costly and/or required too much time to apply; (3) the most effective method was not as effective at certain times of the year when it was most needed; (4) there was a lack of knowledge on which control methods were most effective; (5) the most effective method required special certification to apply or was too restrictive to use; (6) users did not feel the most effective method was as humane or ecologically safe as alternatives; (7) the presence of endangered species often reduced or eliminated the use of the most effective method; (8) damage frequently occurred in an organic field for which the use of the most effective method was not allowable; or (9) other response.

Objective 6 involved ranking where the greatest advancements and research are needed to better manage wildlife pests. Possible responses included: (1) greater knowledge on the biology of the species; (2) greater knowledge on the impact of control methods to the environment; (3) greater knowledge on the economic damage caused by the species; (4) greater advancements in control methods; and (5) a greater understanding of how the juxtaposition of crop fields and natural areas influences the distribution and population dynamics of the species.

We were also interested in the appeal of various control methods to individuals involved in wildlife pest control (Objective 7). The proposed control methods are the same as those listed for Objective 5.

Objective 8 addressed the level of use of an IPM approach for controlling wildlife damage. We were also interested in why survey participants believed that some individuals did not use an IPM approach. Possible responses included: (1) most individuals do use an IPM approach; (2) they prefer to use a single method that has proven effective; (3) they are not aware of what an IPM program is or how it is implemented; (4) there is a lack of effective tools to control some pests, thereby eliminating the possibility of implementing an IPM program; (5) there is a lack of research indicating the effectiveness of an IPM program; (6) there is a lack of cost–benefit studies showing the potential financial savings using an IPM program; and (7) other reasons.

For Objective 9, we wanted to determine the most important attributes for wildlife pest control methods. Survey participants were allowed to rank possible outcomes from 1–5, with 5 being most important and 1 being least important; ranks could be used only once. Possible attributes included: (1) efficacy; (2) quick and inexpensive to apply; (3) environmentally safe; (4) humane; and (5) minimal hazard to the applicator.

Statistical analysis

We used multiple techniques for analysis depending on the data format. For continuous rank data with 1 explanatory variable (Objectives 1–2, 6–7 and 9), we used the Kruskal–Wallis test (Zar 1999). For Objective 3, we had 2 nominal variables (pest and crop), so we use a 2-way analysis of variance (ANOVA) to test the influence of the 2 explanatory variables and their interaction (Zar 1999). For both Kruskal–Wallis tests and 2-way ANOVAs, when a model was significant, we used Fisher's least significant difference *post hoc* test to determine which values were different (Zar 1999). In addition, we were interested in testing for differences in ranks for selected wildlife pests for Objectives 1 and 2. For this, we used a Mann–Whitney *U*-test (Zar 1999) for each of the pests that yielded greater than 5% of the responses.

For nominal responses (Objectives 4–5 and 8), we used Fisher's exact test (i.e. test of independence [Zar 1999]) when we had 2 nominal variables, and the exact multinomial test (i.e. goodness-of-fit test [McDonald 2009]) when we had 1 nominal variable. When these tests indicated a significant difference, we used multiple Fisher's exact tests or exact binomial tests (McDonald 2009) to determine which responses were different. We used $\alpha = 0.05$ for all tests.

RESULTS

Because the survey was sent to specific individuals as well as to county Agricultural Commissioner and Cooperative Extension offices, we do not have a count of potential survey participants (i.e. some offices had multiple individuals qualified to take the survey). As such, we cannot calculate a response rate. However, we were able to track the number of individuals who initiated ($n = 180$) and completed ($n = 143$) the survey. The majority of the responses came from California Agricultural Commissioner offices (31%) and UCCE (41%). Every county in the state was represented by at least 1 survey participant (see Baldwin *et al.* 2011b for details).

Common wildlife pests

Birds, pocket gophers, ground squirrels, voles, wild pigs (*Sus scrofa* Linnaeus, 1758) and coyotes were frequently listed as top wildlife pests in California (see Baldwin *et al.* 2011b for complete results). Comparison of these 6 pest groupings indicated significantly different rankings ($\chi_5 = 66.0$, $P < 0.001$). Of these pests, ground squirrels ($\bar{x} = 1.31$) and pocket gophers ($\bar{x} = 1.09$) were the highest ranked, followed by birds ($\bar{x} = 0.67$), coyotes ($\bar{x} = 0.63$), wild pigs ($\bar{x} = 0.47$) and voles ($\bar{x} = 0.37$) (Table 1).

The wildlife species deemed most in need of advancements in control were similar to those that resulted in the greatest number of complaints (Table 1). The model comparing needed advancements in control methods to species was significant ($\chi_5 = 37.5$, $P < 0.001$). Of these pests, ground squirrels ($\bar{x} = 1.10$) were still the highest ranking pest (Table 1). However, they did not differ from either pocket gophers ($\bar{x} = 1.02$) or birds ($\bar{x} = 1.07$). Voles received the lowest ranking ($\bar{x} = 0.41$; Table 1). Of all of the pests, only wild pigs (Mann–Whitney $U = 6872.5$, $P = 0.022$) and birds (Mann–Whitney $U = 6458.5$, $P = 0.005$) scored significantly higher in the area of needed advancements (Table 1).

Economic damage by common wildlife pests

Economic damage estimated for the 6 common wildlife pests varied ($F_{47,819} = 5.95$, $P < 0.001$), as pest ($F_{5,819} = 11.83$, $P < 0.001$), crop ($F_{7,819} = 5.55$, $P < 0.001$) and a crop × pest interaction ($F_{35,819} = 4.83$, $P < 0.001$) were all significant factors. Of primary interest was the crop × pest interaction (Table 2). For example, coyotes predictably caused an extensive loss in rangeland profits (8.9%) but not in most other commodities (≤3.9%). Birds caused extensive damage in grape (9.0%), nut (9.6%) and berry crops (5.7%), but caused little damage in rangeland or alfalfa fields (≤0.5%; Table 2). Voles (11.3%) and pocket gophers (8.8%) were quite damag-

Table 1 Mean rank scores for the 6 wildlife species in California most frequently listed as 1 of the top 3 wildlife pests resulting in the greatest number of complaints annually (Frequent) as well as most in need of research to develop more effective methods of control (Need). Multiple comparisons (MC) using Fisher's least significant difference were conducted to test for differences in rank scores across species for both Frequent and Need questions. The difference in rank scores for both Frequent and Need responses are also provided to show potential contrasts

	Frequent		Need		
Wildlife pest	Rank†	MC‡	Rank†	MC‡	Difference
Ground squirrel	1.31	A	1.10	A	–0.21
Pocket gopher	1.09	A	1.02	AB	–0.07
Bird	0.67	B	1.07	A	0.40*
Coyote	0.63	B	0.61	CD	–0.02
Wild pig	0.47	BC	0.76	BC	0.29*
Vole	0.37	C	0.41	D	0.04

†For each survey participant, the highest ranking pest received a score of 3, the second highest ranking pest received a score of 2 and the third highest ranking pest received a score of 1. All other pests received a score of 0. ‡Means with the same letter did not differ ($P < 0.05$). *Differences between 'Frequent' and 'Need' scores were significant ($P < 0.05$).

Table 2 Mean rank scores and estimated percent loss in profit caused by the 6 most damaging wildlife pests across 8 common agricultural commodity groupings in California. Differences in rank scores were assessed (Fisher's least significant difference) across species within commodity groupings as well as across commodity groupings within each pest species (Comm.)

	Nuts				Tree fruit				Berries			
Wildlife pest	Rank†	% loss‡	Species§	Comm.¶	Rank†	% loss‡	Species§	Comm.¶	Rank†	% loss‡	Species§	Comm.¶
Birds	1.76	9.6	AB	X	1.13	5.0	AB	Y	1.27	5.7	A	XY
Pocket gophers	1.42	6.1	AB	XY	1.32	5.3	A	XY	1.30	5.3	A	XY
Ground squirrels	1.78	8.7	A	X	1.34	5.3	A	Y	1.14	4.5	AB	Y
Voles	1.22	4.2	B	Y	1.23	4.4	AB	Y	1.00	3.5	AB	YZ
Wild pigs	1.82	10.0	AB	X	1.27	6.4	AB	X	1.25	6.9	AB	X
Coyotes	0.60	1.5	C	Y	0.74	2.5	B	Y	0.69	2.3	B	Y
	Grapes				Vegetable and row crops				Alfalfa			
Wildlife pest	Rank†	% loss‡	Species	Comm.¶	Rank†	% loss‡	Species§	Comm.¶	Rank†	% loss‡	Species§	Comm.¶
Birds	1.75	9.0	A	X	1.11	4.2	A	Y	0.20	0.5	C	Z
Pocket gophers	1.48	6.7	AB	XY	1.40	5.8	A	XY	1.68	8.8	AB	X
Ground squirrels	1.20	4.6	BC	Y	1.37	5.5	A	Y	1.33	5.5	B	Y
Voles	1.00	2.9	BC	YZ	1.36	5.7	A	Y	2.08	11.3	A	X
Wild pigs	1.58	7.7	AB	X	1.29	6.3	A	X	1.20	6.0	B	X
Coyotes	0.87	2.6	C	Y	0.44	1.1	B	Y	0.44	1.4	C	Y
	Rangelands				Dairy and feedlots							
Wildlife pest	Rank†	% loss‡	Species	Comm.¶	Rank†	% loss‡	Species§	Comm.¶				
Birds	0.00	0.0	C	Z	1.11	5.0	A	Y				
Pocket gophers	1.07	4.3	B	YZ	0.56	1.9	AB	Z				
Ground squirrels	1.73	8.4	A	X	0.94	2.9	AB	Y				
Voles	1.38	6.6	AB	Y	0.25	0.6	B	Z				
Wild pigs	1.70	8.2	A	X	0.38	2.5	B	Y				
Coyotes	1.73	8.9	A	X	0.93	3.9	AB	Y				

†The higher the rank, the greater the estimated damage. A score of 3, 2, 1 and 0 meant >15%, 5%–14%, <5% and 0% reduction in profits, respectively. ‡Actual estimates of loss were determined by using the median % reduction in profit value for each respective rank (e.g. ranks of 3, 2, 1 and 0 equated to loss estimates of 20%, 10%, 2.5% and 0%, respectively) except for heavy damage for which we used 20% as the estimate of damage for this rank. §Means in the same column with the same letter did not differ ($P < 0.05$). ¶Means for the same species with the same letter did not differ ($P < 0.05$).

ing in alfalfa, while ground squirrels and wild pigs were very damaging in rangelands (8.4% and 8.2%, respectively) and nut orchards (8.7% and 10.0%, respectively; Table 2). As such, damage caused by these pests should not be expected to be similar across commodities.

Common forms of damage

We observed a difference in the most common forms of damage for birds, pocket gophers, ground squirrels and coyotes (exact multinomial test, $P < 0.001$), although not for voles or wild pigs (exact multinomial test, $P \geq 0.135$; Table 3). For birds and ground squirrels, loss of crop production through direct consumption of fruit, nut, seed or vegetation (77% and 69% of responses, respectively) was the most common form of damage (Table 3). For pocket gophers, loss of vigor or direct death of the plant (70%) was the primary form of damage, while for coyotes, depredation of livestock (67%) and damage to irrigation infrastructure (31%) were the primary and secondary concerns (Table 3).

Methods of control

We observed a significant difference in responses for the methods used most frequently as well as for those deemed most effective for all species (exact multinomial test, $P < 0.001$). For birds, frightening devices were used most frequently (68% of responses), while frightening devices, exclusionary devices and shooting were considered most effective (29%, 27% and 17%, respectively; Table 4). Toxicants were used most frequently (85%) and were considered the most effective method of control for ground squirrels (77%). For pocket gophers, toxicants were used most frequently (57%), while toxicants, traps and fumigants were considered most effective (40%, 30% and 19%, respectively). The use of toxicants was both the most frequently used method (68%) and considered most effective (63%) for controlling voles. For wild pigs, shooting and trapping were both the most frequently used (61% and 26%, respectively) and most effective (50% and 28%, respectively) methods of control. Shooting was also the most frequently used method (68%) for controlling coyotes. Shooting and trapping (34% and 44%, respectively; Table 4) were considered equally effective.

We observed no significant difference between the methods used most frequently and those deemed most effective for pocket gophers, ground squirrels, voles or wild pigs (Fisher's exact test, $P \geq 0.068$; Table 4). However, we did observe a significant difference for birds (Fisher's exact test, $P < 0.001$) and coyotes (Fisher's exact test, $P = 0.050$). For birds, this difference was driven by a lower percentage of respondents who

Table 3 The number (No.) and percentage (%) of responses (in relation to the pest species) of the most common forms of damage for the 6 most frequently identified wildlife pests of California agriculture

	Bird†			Pocket gopher†			Ground squirrel†			Vole‡			Wild pig‡			Coyote†		
Form of damage§	No.	%	MC	No.	%	MC	No.	%	MC	No.	%	MC	No.	%	MC	No.	%	MC
Production	41	77	A	9	15	B	49	69	A	10	34		10	38		1	3	C
Mortality	2	4	BC	43	70	A	12	17	B	14	48		4	15				
Irrigation	1	2	C	9	15	B	9	13	B	5	17		4	15		12	31	B
Disease	8	15	B				1	1	C				8	31				
Depredation	1	2	C													26	67	A

†Values in the same column with the same letter did not differ ($P < 0.05$). ‡There was no significant difference ($P > 0.05$) in the reported forms of damage for this species. §Forms of damage include: production = loss of crop production through direct consumption of fruit, nut, seed or vegetation; mortality = loss of vigor or direct mortality of plant; irrigation = damage to irrigation infrastructure or loss of water down burrow system; disease = disease transmission or consumption or contamination of feed in dairies and feedlots; and depredation = depredation of livestock.

felt that frightening devices were effective (frequency = 68%, effective = 29%; Fisher's exact test, $P < 0.001$), and a greater percentage of individuals who thought shooting was effective (frequency = 4%, effective = 17%; Fisher's exact test, $P = 0.025$; Table 4). The difference for coyotes was driven primarily by a lower percentage of respondents who felt that shooting was an effective control method (34%) as compared to the percentage who listed it as the most frequently used method (68%; Fisher's exact test, $P = 0.008$; Table 4).

When assessing why survey participants believed that the most frequently used and most effective methods differed, we observed no significant difference among any of the responses for ground squirrels or voles (exact multinomial test, $P \geq 0.132$; Table 5). However, responses did differ for birds (exact multinomial test, $P < 0.001$), pocket gophers (exact multinomial test, $P < 0.001$), wild pigs (exact multinomial test, $P = 0.031$) and coyotes (exact multinomial test, $P = 0.044$). For these pests, the most effective method was frequently stated to be too costly (43%, 40%, 33% and 18% for responses for birds, pocket gophers, wild pigs and coyotes, respectively; Table 5). Other common responses were that the most effective method often required special certification to apply or was too restrictive to use (41%, 27% and 22% for coyotes, birds and wild pigs, respectively; Table 5), and that there was a lack of knowledge on which control method was most effective (28% and 27% for wild pigs and pocket gophers, respectively; Table 5). Other responses were rarely listed as important factors (Table 5).

Needed advancements

Areas of needed advancement and research in control methods differed for all wildlife species ($\chi_4 \geq 26.0$, $P < 0.001$). For these species, greater advancements in control methods were ranked as a top research priority ($\bar{x}$ = 3.79–4.66; Table 6). A better understanding of the economic damage caused by wild pigs ($\bar{x} = 3.58$) and the influence of the juxtaposition of crop fields and natural areas on the distribution and population dynamics of wild pigs ($\bar{x} = 3.11$) and voles ($\bar{x} = 3.36$) were also considered high priorities (Table 6). A greater understanding of the biology of damaging wildlife species ($\bar{x}$ = 2.10–2.91) and greater knowledge of the impact of control methods on the environment ($\bar{x}$ = 2.35–2.92) were often the lowest scoring responses (Table 6).

Preferred control methods

We found that the appeal of various control methods was not equivalent ($\chi_9 = 80.2$, $P < 0.001$). Collectively, toxicant use ($\bar{x} = 4.00$), biocontrol ($\bar{x} = 3.74$) and trapping ($\bar{x} = 3.71$) were considered the most appealing methods of control (Table 7). The use of frightening ($\bar{x} = 3.21$) and gas explosive devices ($\bar{x} = 2.92$) were least appealing (Table 7).

Use of integrated pest management for wildlife pest control

Survey respondents felt that most individuals responsible for wildlife damage control in agriculture currently rely on an IPM approach (69 respondents) as opposed to a single control method (44 respondents; exact binomial test, $P = 0.024$). Reasons for not using an IPM approach varied (exact multinomial test, $P < 0.001$), although the primary reasons provided were a preference for using a single method that has proven effective (43% of respondents) and a lack of effective control methods for managing wildlife pests, thereby eliminating the possibility of following an IPM program (30%; Table 8).

Preferred attributes of control methods

The rankings associated with various attributes of control methods were not equivalent ($\chi_4 = 278.8$, $P < 0.001$). Collectively, efficacy was the most important attribute ($\bar{x} = 4.50$; Table 9). Methods that were quick and inexpensive to apply were also highly preferred ($\bar{x} = 3.67$), while the humaneness of a control method was least important ($\bar{x} = 1.64$; Table 9).

DISCUSSION

Wildlife pests cause extensive damage to California agriculture (Shwiff *et al.* 2009). Of these pests, the California ground squirrel has long been considered among the most damaging (Marsh 1998). Ground squirrels were a particularly important pest in nut and tree fruit crops, for which consumption of nuts and fruits was the primary form of damage (Table 3). In fact, ground squirrels were among the highest ranking pests with respect to the amount of damage caused (Table 2), with previous estimates of damage ranging from US$20–$28 million annually (Marsh 1998). The primary method for controlling ground squirrels was the use of toxicants (85%; Table 4); this approach was also deemed most effective (77%; Table 4). Toxicants can be highly effective and are less expensive to apply than other alternatives (Salmon *et al.* 2000, 2007). However, burrow fumigation is also highly effective (Salmon *et al.* 1982; Baldwin & Holtz 2010) and is typically more effective than toxicants in early spring when ground squirrels are eating primarily green foliage. This preference for green foliage limits their consumption of grain-based toxi-

Table 4 A comparison of the number and percentage of responses for control methods used most frequently (Freq) and those considered most effective (Effect) for managing common wildlife pests of California agriculture

	Bird[†]							Pocket gopher						
Control method	Freq[‡]	%	MC[§]	Effect[‡]	%	MC[§]	Dif[¶]	Freq[‡]	%	MC[§]	Effect[‡]	%	MC[§]	Dif[¶]
Toxicant	1	2	C	4	8	CD	3	35	57	A	23	40	A	–12
Fumigant								4	7	C	11	19	A	7
Trap	1	2	C	5	10	BCD	4	17	28	B	17	30	A	0
Habitat modification	3	5	BC	3	6	CD	0	3	5	C	2	4	B	–1
Biocontrol	1	2	C	0		D	–1	0		C	2	4	B	2
Exclusion	10	18	B	14	27	AB	4	0		C	1	2	B	1
Chemical repellent	0		C	2	4	CD	2							
Frightening device	38	68	A	15	29	A	–23*							
Explosive								2	3	C	0		B	–2
Shooting	2	4	C	9	17	ABC	7*	0		C	1	2	B	1

	Ground squirrel							Vole						
Control method	Freq[‡]	%	MC[§]	Effect[‡]	%	MC[§]	Dif[¶]	Freq[‡]	%	MC[§]	Effect[‡]	%	MC[§]	Dif[¶]
Toxicant	62	85	A	55	77	A	–7	21	68	A	19	63	A	–2
Fumigant	3	4	B	10	14	B	7	0		B	0		C	0
Trap	2	3	B	1	1	C	–1	3	10	B	2	7	BC	–1
Habitat modification	1	1	B	2	3	C	1	7	23	B	7	23	BC	0
Biocontrol	3	4	B	1	1	C	–2	0		B	0		C	0
Exclusion								0		B	0		C	0
Chemical repellent								0		B	1	3	BC	1
Frightening device								0		B	1	3	BC	1
Explosive	1	1	B	0		C	–1							
Shooting	4	5	B	2	3	C	–2							

	Wild pig							Coyote[†]						
Control method	Freq[‡]	%	MC[§]	Effect[‡]	%	MC[§]	Dif[¶]	Freq[‡]	%	MC[§]	Effect[‡]	%	MC[§]	Dif[¶]
Toxicant								1	3	C	2	6	B	1
Fumigant								0		C	0		B	0
Trap	8	26	AB	9	28	AB	1	9	24	B	14	44	A	5
Habitat modification	1	3	C	2	6	BC	1	1	3	C	2	6	B	1
Exclusion	2	6	BC	5	16	BC	3	1	3	C	2	6	B	1
Frightening device	1	3	C	0		C	–1	0		C	1	3	B	1
Shooting	19	61	A	16	50	A	–3	25	68	A	11	34	A	–14*

[†]The proportion of responses for control methods used most frequently and those deemed most effective differed ($P < 0.05$). [‡]Data provided includes the number of responses for each species. [§]MC, multiple comparisons. All comparisons were conducted using the exact multinomial test. Control methods in the same column with the same letter did not differ ($P < 0.05$). [¶]The difference (Dif) in the number of responses by pest group between control methods listed to be most frequently used and those listed to be most effective for wildlife pest control. Proportions that were significantly different are indicated with *.

Table 5 A comparison of the number (No.) and percentage (%) of responses as to why survey participants believed that the most frequently used methods and the most effective methods to control the most common wildlife pests of California agriculture differed. Multiple comparisons (MC) were assessed for each species using the exact multinomial test when significant differences occurred

	Bird			Pocket gopher			Ground squirrel			Vole			Wild pig			Coyote		
Reason†	No.	%	MC‡	No.	%	MC‡	No.	%	MC§	No.	%	MC§	No.	%	MC‡	No.	%	MC‡
Cost	16	43	A	12	40	A	6	19		3	30		6	33	A	3	18	AB
Timing	1	3	C	0		B	6	19		1	10		2	11	AB	1	6	AB
Knowledge	3	8	BC	8	27	A	8	26		4	40		5	28	AB	1	6	AB
Restrictive	10	27	AB	4	13	AB	6	19		1	10		4	22	AB	7	41	A
Inhumane	1	3	C	4	13	AB	2	6		0			1	6	AB	3	18	AB
Endangered	5	14	BC	1	3	B	1	3		1	10		0		B	2	12	AB
Organic	1	3	C	1	3	B	2	6		0			0		B	0		B

†Possible reasons include: cost = the most effective method was too costly and/or required too much time to apply; timing = the most effective method was not as effective at certain times of the year when it was most needed; knowledge = there was a lack of knowledge on which control methods were most effective; restrictive = the most effective method required special certification to apply or was too restrictive to use; inhumane = users did not feel the most effective method was as humane or ecologically safe as alternatives; endangered = the presence of endangered species often reduced or eliminated the use of the most effective method; organic = damage frequently occurred in an organic setting for which the use of the most effective method was not allowable. ‡Control methods with the same letter in the same column did not differ ($P < 0.05$). §The number of responses for this species did not differ ($P > 0.05$).

Table 6 Mean rank scores in areas of needed research for the 6 most frequently listed wildlife pests of California agriculture. Multiple comparisons (MC) using Fisher's least significant difference were conducted to test for differences in rank scores within each species

	Bird		Pocket gopher		Ground squirrel		Vole		Wild pig		Coyote	
Response†	Rank‡	MC§	Rank‡	MC§	Rank‡	MC§	Rank‡	MC§	Rank‡	MC§	Rank‡	MC§
Biology	2.46	BC	2.40	C	2.17	C	2.91	BC	2.15	D	2.10	D
Control methods	4.66	A	4.41	A	4.22	A	4.21	A	3.79	A	4.37	A
Economic damage	2.91	B	3.02	B	3.11	B	2.71	BC	3.58	AB	3.26	B
Environment	2.35	C	2.62	BC	2.92	B	2.52	C	2.46	CD	2.76	BC
Juxtaposition of habitat	2.77	BC	2.75	BC	2.79	B	3.36	B	3.11	BC	2.61	CD

†Responses include: biology = greater knowledge in biology of the pest; control methods = greater advancements in control methods of this pest; economic damage = greater knowledge of the economic damage caused by this pest; environment = greater knowledge on the impact of available pest control methods to the environment; and juxtaposition of habitat = greater understanding of how the juxtaposition of crop fields and natural areas influences the distribution and population dynamics of the pest. ‡Ranks ranged from 1–5 with 5 indicating most important and 1 indicating least important; ranks could be used only once per species. §Means in the same column with the same letter did not differ ($P < 0.05$).

cants, thereby making burrow fumigation an essential component of in IPM program.

Although tools like toxicants and burrow fumigation are effective in many situations, they do not solve all ground squirrel problems. For example, ground squirrels can cause substantial damage in almond orchards. Toxicants are not effective in these orchards during the summer given the abundance of a more preferred food (i.e. almonds; O'Connell 1994). Burrow fumigation is also not effective at this time given relatively dry soil conditions, and most other options are less effective or too costly and time-consuming to implement (e.g. trapping, Horn & Fitch 1946; explosive devices, Sullins & Sullivan 1992). The development of a control method that could effectively reduce ground squirrel damage in this situation would be highly useful to many growers (Table 6).

Table 7 Mean rank scores indicating the appeal of each of the below-listed wildlife pest control methods used in California agriculture. Multiple comparisons (Fisher's least significant difference) were conducted to test for differences in rank scores across each control method

Control method	Rank[†]	Multiple comparison[‡]
Toxicant	4.00	A
Biocontrol	3.74	AB
Trap	3.71	B
Habitat modification	3.57	BC
Fumigant	3.51	BCD
Shooting	3.40	CDE
Exclusion	3.31	CDE
Repellent	3.25	DE
Frightening device	3.21	EF
Explosive device	2.92	F

[†]Possible ranks ranged from 1 to 5, with 5 indicating highly desirable and 1 indicating highly undesirable. [‡]Means with the same letter did not differ ($P < 0.05$).

Like ground squirrels, pocket gophers cause extensive damage to a wide variety of crops (Table 2). However, in contrast to ground squirrels, primary pocket gopher damage is attributed to a loss in vigor or direct death of plants (Table 3). Although pocket gopher damage is fairly consistent across most crops, damage was highest in alfalfa (8.8% loss; Table 2), which is consistent with other investigations (Lewis & O'Brien 1990; Messmer & Schroeder 1996).

The primary method for controlling pocket gophers in California was the application of toxicants (57%), followed by trapping (28%) and burrow fumigation (7%; Table 4). The application of toxicants is generally considered to be the quickest and least expensive form of control for pocket gophers, particularly if the toxicant is applied via an artificial burrow builder machine (Marsh 1992). The use of burrow fumigation (primarily aluminum phosphide) and trapping are generally considered to be more labor intensive, time-consuming and costly, and are used less frequently in agricultural fields (Marsh 1992; Engeman & Witmer 2000).

Although toxicants were frequently used (57%) for pocket gopher control, a noticeably lower percentage of respondents considered it to be the most effective method (40%), while we saw a substantial increase in the percentage of respondents who named fumigation as the most effective approach (frequency = 7%, effective = 19%); trapping remained consistent (frequency = 28%, effective = 30%). The efficacy of toxicants has varied tremendously across studies (e.g. 0%–100%; Tickes *et al.* 1982; Evans *et al.* 1990), likely due to a variety

Table 8 A comparison of the number (No.) and percentage (%) of responses as to why survey participants believed that some individuals do not use an integrated pest management (IPM) program for controlling wildlife pests of California agriculture

Response	No.	%	MC[†]
They prefer to use a single method that has proven effective.	36	43	A
Using more than a single method that has proven effective is not possible.	25	30	A
They are not aware of what an IPM program is or how it is implemented.	9	11	B
Cost-benefit studies illustrating the cost effectiveness of IPM are lacking.	9	11	B
There is a lack of research indicating the effectiveness of IPM.	4	5	B

[†]MC, multiple comparisons. All comparisons were conducted using the binomial exact test. Responses with the same letter did not differ ($P < 0.05$).

Table 9 Mean rank scores indicating which attributes of a control method are most important to agricultural clientele in California. Multiple comparisons (Fisher's least significant difference) were conducted to test for differences in rank scores across each attribute

Attribute	Rank†	Multiple comparison‡
Efficacy	4.50	A
Quick and inexpensive	3.67	B
Hazard to applicator	2.74	C
Environmentally safe	2.53	C
Humane	1.64	D

†Possible ranks ranged from 1–5 with 5 indicating most important and 1 indicating least important. ‡Means with the same letter did not differ ($P < 0.05$).

of factors including bait type and bait-applicator experience (Baldwin 2014; Baldwin *et al.* 2011a). Finding materials or methods that make toxicants consistently efficacious would likely be highly desirable to individuals managing pocket gopher damage.

Currently, trapping and burrow fumigation provide more consistent results and are often considered more effective than toxicants for pocket gopher control (Lewis & O'Brien 1990; Baker 2004). However, the cost of trapping and burrow fumigation is considered too high by most growers (Table 5). In addition, many individuals do not realize that trapping and burrow fumigation can be more effective than toxicants (Table 5); this should be considered more thoroughly as greater awareness could increase the effectiveness of pocket gopher control. Regardless, most survey respondents listed advancements in control methods as the primary area of need with respect to pocket gopher management (Table 6). Pocket gopher control can be quite challenging given their almost exclusive use of underground burrow systems, which makes targeting this pest difficult. Current control techniques are either quick to apply (e.g. toxicant application) or consistently efficacious (e.g. trapping and burrow fumigation), but not both. The development of a tool that is both quick to apply and highly effective would greatly assist pocket gopher management.

Primary bird pests included crows, blackbirds and starlings (Baldwin *et al.* 2011b). Individually, none of these bird species were considered as great a pest as the other 5 pest groups (Baldwin *et al.* 2011b), but collectively, they were considered substantial pests (Table 1). In fact, we observed significantly higher mean rank scores for needed advancements in control methods ($\bar{x}$ = 1.07) compared to the frequency of complaints ($\bar{x}$ = 0.67), indicating that bird damage control is a substantial area of concern.

As with pocket gophers and ground squirrels, birds cause extensive and quite varied forms of damage, although the consumption of nuts, fruits, seeds and vegetation was the primary form of damage reported (Table 3). This was further illustrated by the large losses estimated in nut (9.6%) and grape (9.0%) crops, where previous estimates of damage have ranged from 0% to 77% for a variety of bird pests (Gebhardt *et al.* 2011). Primary methods used to limit this damage included frightening devices (68%) and physical exclusion (18%). Our data clearly indicate that frightening devices were not the preferred method for bird control in many situations, as we observed a 57% decrease in the number of individuals who thought frightening devices were the most effective method versus those who thought they were the most frequently used method (Table 4). Rather, we observed an increase in preference for lethal control options (i.e. shooting, and, to a lesser extent, trapping and toxicants; Table 4). Although these lethal control methods were deemed more effective, there are many restrictions involved in the take of most bird species. For example, a federal depredation permit is required to trap or shoot most bird species, and no avicides are currently available for use by anyone other than USDA–Wildlife Services. These greater costs and restrictions appear to limit the use of lethal approaches for bird control. Given the high cost of exclusion, the dissatisfaction associated with frightening devices, and substantial restrictions associated with lethal removal approaches, it is not surprising that most respondents identified a desire for better control methods (Tables 1 and 6). Perhaps 1 solution could entail developing more efficient and economical methods for applying exclusionary netting for birds. Netting is considered highly efficacious and does not require the removal of birds (Fuller-Perrine & Tobin 1993). A reduction in costs for application and difficulties in erecting netting could greatly increase the utility of this approach.

Coyotes typically yielded different concerns than other species, given their predatory nature. Not surprisingly, depredation of livestock was the primary concern, with losses by coyotes greatest in rangelands (8.9%), and, to a lesser extent, dairies and feedlots (3.9%; Table 2). Similar losses have been reported throughout the USA (e.g. reported cattle losses to USDA–Wildlife Services = US$52.3 million in 2010; USDA 2011). Damage to irrigation infrastructure through chewing was also a large concern (Table 3), resulting in extensive damage each year (Connolly 1992). Nonetheless, greater information on economic damage caused by coyotes is needed to gain a better grasp of the impact of this pest on agricultural commodities (Table 6).

Coyotes were most frequently controlled through shooting. However, we observed a significantly lower proportion of individuals who felt that shooting was the most effective form of control (Table 4). Although not significantly different from shooting, trapping was considered the most effective control method for coyotes (Table 4). Primary traps used to capture coyotes throughout most of the USA include foothold traps and snares (Andelt *et al.* 1999). However, these traps are not currently legal for use in most situations in California. This restriction likely explains why traps are not used more frequently (Table 5). The loss of this management tool, along with the loss of sodium cyanide in M-44 devices and Compound 1080 in Livestock Protection Collars (Connolly 2002), has resulted in few options for lethal coyote control, thereby leading to the need for new and more effective control methods (Table 6).

Wild pigs are a rapidly expanding problem throughout the USA (West *et al.* 2009). Rankings for needed advancements in control were significantly higher than the frequency of complaints for this pest (Table 1), indicating a strong belief that alternative or more efficient methods of damage control are needed (Table 6). Currently, trapping and shooting are the most frequently used methods of control and are considered to be the most effective as well (Table 4). These methods can effectively remove wild pigs but require much effort (West *et al.* 2009). In addition, they are only effective long term if adjacent property owners work in a collaborative manner to reduce population size. Otherwise, populations quickly rebound and reinvade (West *et al.* 2009). A better understanding of the influence of the juxtaposition of adjacent habitats would likely increase control efforts, as wild pigs have different requisites for resting, escape and foraging habitat (Schauss *et al.* 1990; Choquenot & Ruscoe 2003). Areas that contain all of these habitat requirements are more likely to house wild pig populations. A better understanding of this relationship could allow landowners to remove 1 or more of these life requisites, thereby reducing the carrying capacity for that area. Alternatively, this information could allow hunters and trappers to focus control efforts on key habitats for wild pigs. This collective information would allow landowners to decrease damage caused by wild pigs and should be an area of fruitful research in the future.

Greater knowledge on these issues is becoming increasingly important given the rapid expansion in the number of pigs over the past 20 years (West *et al.* 2009). The impact of this increase is reflected in damage estimates to a variety of agricultural commodities, including nuts, grapes and rangelands (Table 2). In fact, the collective damage estimate from wild pigs was greater than that of the other wildlife pests included in this survey (Baldwin *et al.* 2011b), with nationwide estimates of damage reported around US$1.5 billion annually (Pimentel *et al*. 2005). Consumption of crops, disease transmission and contamination of livestock and human foods are typically the primary forms of damage caused by wild pigs to agricultural commodities (West *et al.* 2009). Although we observed no significant difference between any of the reported forms of damage for wild pigs (Table 3), these were the components that scored highest and are likely the primary forms of damage caused by wild pigs in California as well.

Of the 6 pest groupings, voles were reported as the least frequent pest and scored lowest on the need for advancements in control methods (Table 1). However, when voles were present, they were responsible for substantial economic losses, particularly in alfalfa, where they caused more damage than any other pest in any other crop (11.3%; Table 2). Nonetheless, damage appears to vary substantially across species and region (e.g. Babińska-Werka 1979; Lewis & O'Brien 1990; Messmer & Schroeder 1996). Based on our findings, vole damage, caused principally by *M. californicus*, appears to be on the moderate to high end of damage caused by vole species, with most of the damage coming in the form of loss of crop production and/or direct death of the plant (Table 3).

Toxicants were the primary method used for vole control (Table 4). As with Utah, toxicants were considered the most effective control method for voles (Messmer & Schroeder 1996). However, in Nevada, cultural practices were the most effective control method (Lewis & O'Brien 1990). Voles are cover dependent; a reduction in cover results in increased predation, which can help regulate vole populations (e.g. Getz *et al.* 2005). The use of habitat modification/cultural practices was the second highest scoring response for voles in our study (Table 4), and should be considered an effective management option in many cropping systems.

Greater advancement in control methods was the primary research need for voles (Table 6). Few options exist to control voles in most crops during the active growing season. Toxicants and habitat modification can effectively control vole populations, but 1 or neither of these approaches may be available in some crops. For example, in alfalfa the only toxicant currently registered for use is zinc phosphide, and it can only be applied once every 6 months. However, voles often exhibit bait shyness with respect to zinc phosphide (Marsh 1987), thereby rendering it ineffective when bait acceptance is low. In addition, habitat modification is not practical, as cover is an inherent characteristic of alfalfa. Similarly, application of most toxicants is not allowable in vineyards or orchards during the growing season when they are often most needed. In these cases, growers are left with few if any control options. The development of an alternative strategy to control voles in these situations is needed.

Collectively, toxicants, biocontrol and trapping were the preferred methods of control for wildlife pests, while frightening and gas explosive devices were the least preferred (Table 7). Overall, these rankings indicate a preference for approaches that have proven more effective yet practical (trapping, Proulx 1997; toxicants, Salmon *et al.* 2000, 2007), while avoiding those that are often less effective (gas explosive devices, Sullins & Sullivan 1992) or require constant implementation and adaptation (frightening devices, Stetson & Baldwin 2010). Biocontrol appears to be the exception, as we are aware of no studies that have shown biocontrol to be an effective management option for controlling wildlife pests in California. Possible explanations for the high ranking are a lack of knowledge on the low efficacy associated with this approach, strong advocacy for biocontrol by environmental and animal welfare organizations, or perhaps simply a strong desire to find a biocontrol method that is efficacious. It should also be pointed out that many efforts at implementing biocontrol have failed miserably in other parts of the world, leading to cataclysmic reductions in native fauna (e.g. Indian mongoose, *Herpestes* spp.; Watari *et al.* 2008; Lewis *et al.* 2011). Therefore, although the reliance on natural predation may lower the costs and environmental risks associated with some alternative control methods, at this time biocontrol does not appear to be an effective option for managing wildlife pests (e.g. Marsh 1992; Witmer 2007).

A perfect control method would be highly efficacious, quick and inexpensive to apply, safe to the environment and the applicator, and humane. Developing control methods that achieve high scores for all of these attributes is a difficult task, so often we must focus our efforts on achieving high levels of success for the most important attributes while attaining acceptable levels for less important attributes. For our respondents, the development of a technique that is efficacious was the most important consideration; methods that are quick and inexpensive to apply were also important (Table 9). This is somewhat counter to our previous findings as we often observed differences in the frequency of use and perceived effectiveness of various control methods (Tables 4 and 5). For most pests, cost was the primary reason provided as to why the more efficacious methods were not used more frequently (Table 5). Certainly, there will be some threshold where cost overrides efficacy. For example, in 1993, almond growers were not willing to spend more than US$59 per ha to reduce crow damage by 50% (Hasey & Salmon 1993). It is likely that costs of more efficacious control methods exceeded this undefined level for many human–wildlife conflicts in this study, which resulted in more frequent use of less efficacious methods.

Most individuals surveyed (61%) indicated a preference for an IPM approach for controlling wildlife pests. Following an IPM program typically provides the best results (Engeman & Witmer 2000; Sterner 2008); such programs have been steadily incorporated into many wildlife control programs. Much time and effort has been spent on advocating the utility of this approach. It is reassuring to note that most survey respondents (89%) felt that a lack of knowledge on the IPM concept was not a limiting factor to its implementation. Likely the greatest step that can be taken to further increase its incorporation into wildlife pest control programs is to develop alternative methods of control for those pests where options are limited (e.g. voles and coyotes). This would likely increase the level of control for most of these pests while reducing the possibility of behavioral (e.g. avoidance of strychnine baits; Marsh 1992) or physiological (e.g. resistance of voles to anticoagulants; Salmon & Lawrence 2006) resistance to the currently available control methods.

ACKNOWLEDGMENTS

This project was funded by the California Department of Food and Agriculture Vertebrate Pest Control Research Advisory Committee. We thank D. Bulls, N. Quinn, D. Stetson and M. Tibbets for assistance in developing and distributing this survey, M. Remmenga for statistical assistance, and S. Shwiff for providing useful comments on survey design. Finally, we would like to thank all survey participants for volunteering their valuable time to complete this survey.

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