Generators such as this are common at cannabis cultivation sites, particularly those in remote forested regions like the Emerald Triangle (Humboldt, Mendocino, and Trinity Counties), CA. Photo Credit: CDFW staff

Example of a large outdoor cultivation in Humboldt County. Photo Credit: Scott Bauer, CDFW

Anthropogenic noise: potential influences on wildlife and applications to cannabis cultivation

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Biological sounds play an important role in activities ranging from territory defense to mate choice to predator avoidance to foraging. Anthropogenic noise can mask these sounds, potentially altering the habitat selection, activity patterns, phenology, and physiology of wildlife species. For example, cannabis (Cannabis sativa or C. indica) cultivation may increase levels of anthropogenic noise given the use of diesel generators, irrigation pumps, and landscaping equipment. To predict how noises associated with cannabis cultivation may influence wildlife in California, we review scientific literature assessing the influences of anthropogenic noise on various species of mammals, birds, herpetofauna, and invertebrates. We then outline potential noises associated with cannabis cultivation and why they may be unique on the landscape and provide recommendations on future research needs.

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The acoustic environment is more than just a collection of auditory signals between individuals, it is an interconnected landscape of information networks consisting of many signalers, receivers, and sounds vital to the fitness of a species (Templeton and Greene 2007; Barber et al. 2010; Read et al. 2013). For example, sounds pertaining to territory defense, mate attraction, or family cohesion (i.e., contact calls) promote reproductive success (Halfwerk et al. 2011a, b; Allen et al. 2016). In songbirds, these sounds are used to assess numerous individuals simultaneously for mate choice, extra-pair copulations, and rival assessment (Barber et al. 2010). Alternatively, sounds announcing the approach of predators (i.e., alarm calls) promote survival of both conspecifics to whom the calls were directed and other species that capitalize on the alarms (Templeton and Greene 2007; Sloan and Hare 2008; Magrath et al. 2015).

Successful acoustic communication requires sounds to 1) move through the environment from senders to receivers and 2) be detectable through background noise (Patricelli and Blickley 2006). There is mounting evidence that noise produced by humans, whether from vehicles, construction equipment, or humming power sources (e.g., generators, power lines,

wind turbines), dramatically increases the amount of background noise, in turn impeding detectability of acoustic signals and negatively impacting the ability of a species to communicate (Fernández-Juricic et al. 2005; Gillam and McCracken 2007; Barber et al. 2010; Kite and Swaddle 2011; Francis and Barber 2013). Masking of biologically relevant sounds can limit mate choice, cause species to abandon territories or potential habitat, negatively impact species' ability to locate food, or cause deleterious physiological effects like hearing loss, raised blood pressure, and increased production of stress hormones (Rabin et al. 2006; Wright et al. 2007; Schaub et al. 2008; Shannon et al. 2014; Ware et al. 2015). In a rural to suburban area where ambient noise levels are 45 – 55 decibels (dB), new sources of anthropogenic noise can begin having deleterious effects when they increase overall noise by just 5 – 10 dB (Dooling and Popper 2007). The specific noise level at which impacts begin to appear, however, depends on the amount of ambient noise and the temporal and spectral overlap between anthropogenic and biological sounds (Dooling and Popper 2007; Halfwerk et al. 2011). Species with low-frequency vocalizations like owls and grouse tend to have the largest spectral overlap with traffic noise, for example, which means these species are more likely to have their mate attraction or territorial defense songs obscured by human-produced noises (i.e., experience a decline in signaling efficiency; Slabbekoorn and Ripmeester 2007; Bunkley et al. 2015).

Cannabis cultivation has the potential to add additional sources of anthropogenic noise into a landscape through, for example, diesel generators, irrigation pumps, climate control systems, landscaping equipment, and vehicles. There is concern that this additional anthropogenic noise may reach the level of take, as defined by the Federal Endangered Species Act (ESA; i.e., an action of or attempt to hunt, harm, harass, pursue, shoot, wound, capture, kill, trap, or collect a species), for sensitive species like the northern spotted owl (*Strix occidentalis occidentalis*) and marbled murrelet (*Brachyramphus marmoratus*; USFWS 2006). For northern spotted owl and marbled murrelet it was determined that disturbance may reach the level of take if 1) project-generated sound exceeds ambient nesting conditions by 20-25 dB, 2) project-generated sound, when added to existing ambient conditions, exceeds 90 dB, or 3) human activities occur within a visual line-of-sight distance of 40 m or less from a nest (USFWS 2006). We note that California's ESA has a narrower definition of take (i.e., any action of or attempt to hunt, pursue, catch, capture, or kill). This could make it more difficult to directly attribute take to anthropogenic noise under the California ESA when compared to the Federal ESA.

Information on the levels of noise produced by cannabis cultivation specifically and the subsequent influences on wildlife species, however, is scant. To predict how anthropogenic noise associated with cannabis cultivation may influence wildlife in California, we reviewed scientific literature that assessed the influences of human-produced noise on species' habitat selection, activity patterns, phenology, and physiology. We then provide recommendations on future research needs.

Habitat selection and Activity Patterns

Mobile animals are often guided by sound, with conspecific signals attracting group members or potential mates, heterospecific signals (i.e., signals from a different species) indicating suitable habitat, and overall soundscape signals providing cues for general orientation (Slabbekoorn and Bouton 2008). Consequently, site abandonment and changes in

habitat selection and activity patterns are among the most detected impacts of noise (Table 1; Francis and Barber 2013). Species ranging from deer to songbirds to frogs have been documented avoiding areas with anthropogenic noise, in turn influencing both fine-scale habitat selection and large-scale patterns of movement (Table 1; Sawyer et al. 2006; Mukhin et al. 2008; Francis et al. 2011; Ware et al. 2015; Caorsi et al. 2017). Further, avoidance or use by one species may lead to avoidance or use by others. This has been documented in nocturnally migrating bird species, where migrant birds listen for the heterospecific calls of resident birds to make decisions about which habitats to use as stopover sites (i.e., the heterospecific attraction hypothesis; Mönkkönen et al. 1990; Mukhin et al. 2008). It has

Table 1. Examples of changes in habitat selection and activity patterns resulting from anthropogenic noise.

Taxa	Species	Response	Source
Mammals	Mule deer (*Odocoileus hemionus*)	Radio-collared deer were more likely to occupy habitat away from noise-producing oil and gas developments than habitat in close proximity; changes in habitat selection happened within 1 year of development and there were no signs of acclimation.	Sawyer et al. 2006
	Sonoran pronghorn (*antilocapra Americana sonoriensis*)	Pronghorn at a military site where there was noise from overflights, ordinance deliveries, and human activity foraged less and stood and traveled more than pronghorn not exposed to military activity.	Krausman et al. 2004
	California ground squirrels (*Otospermophilus beecheyi*)	Close to wind turbines, where noise levels were higher than control sites (110.2 dB vs. 79.8 dB), squirrels exhibited increased rates of vigilance and were more likely to return to their burrows during alarm calling (i.e., increased caution).	Rabin et al. 2006
	Prairie dogs (*Cynomys ludovicianus*)	When exposed to road playback noise (77 dB at 10m), the number of prairie dogs aboveground decreased by 21%, the proportion of individuals foraging decreased by 18%, and vigilance increased by 48%. These results were consistent across a 3-month period suggesting there was no habituation.	Shannon et al. 2014
	Bat community	Bat species emitting low frequency (< 35 kHz) echolocation calls had a 70% reduction in activity levels at loud compressor sites (70 – 82 dB) vs. quieter well pads (53 – 70 dB). Bat species emitting high frequency calls did not show altered activity levels.	Bunkley et al. 2015
	Greater mouse-eared bat (*Myotis myotis*)	Successful foraging bouts decreased, and search time increased with proximity to acoustically simulated highway noise. At 7.5m from the noise source, it took the bats 5x longer to find their prey, which they locate by listening for faint rustling sounds.	Siemers and Schaub 2011
Birds	American robin (*Turdus migratorius*)	Foraging success was reduced when the auditory cues that robins rely on to locate buried worms were obscured by white noise (61 dB).	Montgomerie and Weatherhead 1997
	Nocturnally migrating birds	To test the effect of noise alone, a "phantom road" was created through an array of speakers broadcasting traffic noise. Among the bird community, 31% avoided using the phantom road as a stopover site during migration and the birds that did use the site showed a decrease in their overall body condition.	Ware et al. 2015
	Grey flycatcher (*Empidonax wrightii*)	Occupancy of flycatchers was lower at sites with 46-68 dB of noise than sites with 32-46 dB of noise.	Francis et al. 2011

Table 1. continued.

Taxa	Species	Response	Source
	White-throated sparrow (*Zonotrichia albicollis*), yellow-rumped warbler (*Dendroica coronata*), and red-eyed vireo (*Vireo olivaceus*)	Passerine density was 1.5x higher at energy sites that did not produce noise than at those that did (48 dB).	Bayne et al. 2008
	Greater sage-grouse (*Centrocercus urophasianus*)	Radio-marked female grouse were more likely to select habitat away from noise-producing oil and gas developments and were 1.3x more likely to occupy sagebrush habitats lacking wells within a 4-km² area.	Doherty et al. 2008
Herpetofauna	Bischoff's tree frog (*Boana bischoffi*) and fine-lined tree frog (*B. leptolineata*)	Both species moved away from playbacks of road noise (played at two intensities- 65 and 75 dB), suggesting the noise resulted in their spatial displacement.	Caorsi et al. 2017

also been documented in marbled newts (*Triturus marmoratus*) and smoot newts (*Lissotriton vulgaris*), which orient towards the calls of species that share similar breeding habitat (Diego-Rasilla and Luengo 2004; Pupin et al. 2007).

Sound is also important in determining how much time and energy a species expends on activities like resting, vigilance, and foraging (Quinn et al. 2006; Rabin et al. 2006; Shannon et al. 2014). Many animals use sound to detect approaching predators or to warn conspecific and heterospecific co-occurring species (e.g., through alarm calls) that a predator is approaching. Quiet environments facilitate detection of these auditory cues, so less time needs to be spent searching for predators. Conversely, noisy environments impede auditory cues resulting in species spending more time and energy on anti-predator behaviors like vigilance and caution (e.g., not traveling far from a burrow; Quinn et al. 2006; Shannon et al. 2014). A positive relationship between noise and predator avoidance has been documented in both mammal and bird species (Quinn et al. 2006; Francis and Barber 2013; Shannon et al. 2014). California ground squirrels (*Otospermophilus beecheyi*), for example, tend to exhibit increased rates of vigilance in noisy environments where their ability to hear conspecific alarm calls is hindered (Rabin et al. 2006). If noise causes ground squirrels to miss just a single conspecific alarm call, then they may underestimate potential threats and in turn, increase their exposure to predation (Sloan and Hare 2008). In chaffinches (*Fringilla coelebs*) and prairie dogs (*Cynomys ludovicianus*), alternatively, noise leads to more time expended on vigilance and less time on foraging (Quinn et al. 2006; Shannon et al. 2014). Delayed response times of ground squirrels and loss of foraging time in chaffinches and prairie dogs demonstrate how noise, through its influence on predator-prey dynamics, can have both immediate (i.e., survival) and long-term (i.e., decreased nutrition/energy) impacts on species' fitness (Frid and Dill 2002).

Lastly, anthropogenic noise may decrease foraging efficiency if the species relies on auditory cues to locate food. Bat species specialized in gleaning arthropods off vegetation or the ground, for example, find prey by passively listening for prey-produced sounds

(Schaub et al. 2008). Thus, in environments with more noise, gleaning bats have fewer successful foraging bouts and spend more time searching for prey (Table 1; Schaub et al. 2008; Siemers and Schaub 2011). Decline of 12 species of bats in California that are either endangered or species of special concern has been correlated to reduced foraging success in noisy environments (Schaub et al. 2008; Siemers and Schaub 2011). Bird species like American robins (*Turdus migratorius*), marsh hawks (*Circus cyaneius*), and barn owls (*Tyto alba*), as well as reptile species like geckos (*Hemidactylus tursicus*), also use auditory cues to detect and locate prey. Like gleaning bats, these species have reduced foraging success in noisy environments where cues are obscured (Knudsen and Konishi 1979; Rice 1982; Sakaluk and Belwood 1984; Montgomerie and Weatherhead 1997).

Phenology and Physiology

To mitigate the negative impacts that anthropogenic noise may have on acoustic communication, many species adjust the frequency structure (i.e., pitch), amplitude (i.e., loudness), or timing of their vocalizations (Table 2; Patricelli and Blickley 2006). Vocal adjustments have been documented in a range of species, including bats, birds, frogs, and insects (Table 2). Brazilian free-tailed bats (*Tadarida brasiliensis*), reed buntings (*Emberiza schoeniclus*), great tits (*Parus major*), cicadas (*Cryptotympana takasagona*), and grasshoppers (*Chorthippus biguttulus*), for example, use higher call frequencies in the presence of anthropogenic noise (Slabbekoorn and Peet 2003; Gillam and McCracken 2007; Gross et al. 2010; Lampe et al. 2012; Shieh et al. 2012). Conversely, various species of frogs often increase or decrease their call rates based on the level of background noise (Lengange 2008; Cunnington and Fahrig 2010; Vargas-Salinas and Amézquita 2013). The benefit of vocal plasticity is that it allows species to adjust to new, noisy conditions (Gross et al. 2010). The hindrance is that it may negatively impact species' fitness by reducing transmission distances (e.g., high frequency signals attenuate faster), increasing the risk of predation or parasitism by making animals more conspicuous, altering energy budgets causing vital information to be lost (e.g., for mate choice), or breaking down signaler-receiver coordination (Luther 2008; Read et al. 2013).

In addition to altering the phenology of a species, exposure to noise can also influence the physiology of a species. Ungulates, bears, whales, game birds, songbirds, and frogs have all been documented to have adverse physiological responses to anthropogenic noise (Table 2; Powell et al. 2006; Rolland et al. 2012; Troianowski et al. 2017). These responses include hearing loss, hypertension (i.e., raised blood pressure), and increased production of glucocorticoids or stress hormones (Wright et al. 2007; Dooling and Popper 2007; Shannon et al. 2016). Increased production of stress hormones can in turn, negatively impact the survival and reproduction of a species by causing decreased immune response, diabetes, or reproductive malfunctions (Kight and Swaddle 2011; Tennessen et al. 2014). Exposure to noise led to increased stress hormone levels in European tree frogs (*Hyla arborea*), for example, which led to an immunosuppressive effect (Troianowski et al. 2017). The severity of a species' physiological responses is likely dependent on season. Northern spotted owl (*Strix occidentalis caurina*) males, for example, had the strongest response to motorcycle noise in May, when feeding themselves, their mates, and their nestlings (Hayward et al. 2011). The physiological response of migratory birds, alternatively, may be most acute mid-migration when maintenance of body condition is particularly imperative (Ware et al. 2015).

Table 2. Examples of phenological and physiological changes associated with anthropogenic noise.

Taxa	Species	Response	Source
Mammals	General	If the inner ear sensory hair cells are damaged, then mammals will experience permanent hearing loss.	Dooling and Popper 2007
	Brazilian free-tailed bats (*Tadarida brasiliensis*)	Bats recorded in the presence of high-frequency sounds used higher call frequencies than bats recorded in silence, which suggests that bats adjusted their echolocation call structure to minimize acoustic interference.	Gillam and Mc-Cracken 2007
	Desert mule deer (*Odocoileus hemionus crooki*) and desert bighorn sheep (*Ovis canadensis mexicana*)	Heart rates of captive animals increased relative to dB levels (from simulated jet aircraft noise) but returned to pre-disturbance levels within 60-180 seconds.	Weisenberger et al. 1996
Birds	House finches (*Carpodacus mexicanus*)	Males increased the low frequency (1.62 kHz) of their songs in areas with higher ambient noise to reduce the masking effects of the noise.	Fernández-Juricic et al. 2005
	Ash-throated flycatcher (*Myiarchus cinerascens*)	Occupancy was not influenced by noise from gas well compressors but bird vocalizations were; and individuals in areas with more noise vocalized at frequencies ~200 kHz higher. Noise levels averaged 37.4 and 56.1 dB at control and treatment sites, respectively.	Francis et al. 2011
	Song sparrows (*Melospiza melodia*)	Males shifted more energy into the higher frequencies of their vocalizations when there was more noise (total ambient background noise ranged from 54.8 – 71.3 dB).	Wood and Yezerinac 2006
	House sparrows (*Passer domesticus*)	Nests in area with large generator noise (68 dB) produced fewer young of lower body mass, and fewer recruits; females also provided young with food less often in noisy area.	Schroeder et al. 2012
	Tree swallows (*Tachycineta bicolor*)	Nestlings exposed to white noise playbacks (65 dB) had begging calls with higher minimum frequencies and narrower frequency ranges. These effects persisted in the absence of noise, suggesting that noise may influence call development. Further, when exposed to playbacks, nestlings were less likely to beg when parents arrived with food.	Leonard and Horn 2008
	Black-capped chickadee (*Poecile atricapillus*)	Noise reduced the number of individuals that could be heard, thus limiting mate choice and rival assessment.	Hansen et al. 2015
	Northern spotted owl (*Strix occidentalis occidentalis*)	Males had highest glucocorticoid response to experimentally applied motorcycle noise in May, when they are generally responsible for feeding themselves, their mates, and their nestlings.	Hayward et al. 2011
	Quail (*Coturnix coturnix*)	When quail were exposed to 116 dB of noise for 4 hours, they experienced hearing loss of up to 50 dB immediately following exposure.	Niemiec et al. 1994
	Greater sage-grouse (*Centrocercus urophasianus*)	Fecal corticosterone metabolite levels were 16.7% higher, on average, at leks where 67.6 dB of road noise was broadcast vs. control leks with no noise. Further, peak male attendance and abundance at noise-treated leks decreased by over 29% when compared to paired controls.	Blickley et al. 2012a, b

Table 2. continued.

Taxa	Species	Response	Source
Herpeto-fauna	Bischoff's tree frog (*Boana bischoffi*)	Advertisement call rates decreased during playbacks of road noise (played at two intensities- 65 and 75 dB) and dominant call frequency decreased when exposed to noise.	Caorsi et al. 2017
	Green frog (*Rana clamitans*), leopard frog (*R. pipiens*), gray treefrog (*Hyla versicolor*)	Call rates were significantly lower at low-noise sites (mean = 43.8 dB) than high-noise sites (mean = 73.2 dB). Further, when traffic noise was broadcast at low-noise sites, green and leopard frog vocalizations changed to having higher frequencies.	Cunnington and Fahrig 2010
	European tree frog (*H. arborea*)	Exposure to traffic playback noise (76 dB) led to increased stress hormone levels and in turn, an immunosuppressive effect.	Troianowski et al. 2017
	Wood frogs (*Lithobates sylvaticus*)	Traffic playback noise (87 dB) increased levels of glucocorticoid hormones in females. It also negatively influenced female travel towards male breeding choruses, highlighting the sublethal impacts of acoustic habitat loss.	Tennessen et al. 2014
	Grey treefrog (*Hyla chrysoscelis*)	Traffic playback noise (70 dB) resulted in female frogs taking longer to localize male calls; females were also less successful in correctly orienting to male signals.	Bee and Swanson 2007
Inverte-brates	Grasshoppers (*Chorthippus biguttulus*)	Compared to males from quiet habitats, males in roadside habitats produced acoustic courtship songs with higher local frequency maximum (6-9 kHz).	Lampe et al. 2012
	Cicada (*Cryptotympana takasagona*)	Cicadas shifted the energy distribution of calling songs to higher frequencies when higher anthropogenic noise.	Shieh et al. 2012

The effects that anthropogenic noises can have on species' habitat selection, activity patterns, phenology, and physiology can culminate in decreased reproductive success. This decrease may be a consequence of limited mate choice, a reduction in pairing success, decreased provisioning rates to offspring, or a decline in offspring survival (Table 2; Francis and Barber 2013). If noise impedes the transmission of bird songs, for example, it may negatively impact mate attraction (Klump 1996; Hansen et al. 2005). If noise impedes parent-offspring communication, alternatively, it may result in young receiving food less often (e.g., if nestlings fail to beg when their parents arrive; Leonard and Horn 2012; Schroeder et al. 2012). Numerous species of birds, including eastern bluebirds (*Sialia sialis*), great tits (*Parus major*), and house sparrows (*Passer domesticus*), are known to produce fewer eggs in noisier areas (Halfwerk et al. 2011b; Kight et al. 2012; Schroeder et al. 2012). Lastly, anthropogenic noise may make it harder for females to detect and locate males, as has been documented in frogs (Bee and Swanson 2007; Tennessen et al. 2014).

FUTURE DIRECTIONS

California's Department of Food and Agriculture (CDFA) identified several potential impacts of the noises associated with cannabis cultivation in their Program Environmental Impact Report (PEIR; CDFA 2017). This noise may result from the use of irrigation pumps, diesel generators, landscaping equipment, equipment and water trucks, worker vehicles, and if a greenhouse has climate control, the heating, ventilation, and air conditioning systems.

As outlined in the PEIR, increased noise and human presence may cause substantial adverse effects on special-status terrestrial wildlife species, and use of mechanical equipment for the cultivation of cannabis may cause excessive ground borne vibration or ground borne noise levels, as well as substantial increases in ambient noise levels in the vicinity of a proposed program activity (CDFA 2017). Upon review, however, CDFA found all noise-related impacts to be "less than significant", stating that in general, the noises resulting from cannabis cultivation would be consistent with other land uses in the area (CDFA 2017). We propose, however, that the noises resulting from cannabis cultivation may differ from those associated with other land uses in the area and warrants further consideration and research.

Determining whether the noises resulting from cannabis cultivation are consistent with other land uses in the area requires an understanding of the noises' duration, loudness (i.e., decibels), and spatial location. Short-term noises from chainsaws, mowers, and vehicles may be consistent with other human-generated noises in an area; however, long-term noises from irrigation pumps, diesel generators, and climate control systems may be new. These long-term noises may adversely affect local fauna not only because they are novel, but also because they are perpetual, meaning they act as a constant impediment to the ability of the species to hear. Loudness of a noise may also play a role in determining impacts, particularly when loudness is considered in relation to ambient noise levels. A generator running at night, for example, likely has greater impacts on surrounding wildlife in a rural area, where ambient noise levels are around 20 dB, than in an urban area, where ambient noise levels are around 40 dB (Dooling and Popper 2007; CDFA 2017).

To date, most mixed-light licenses have been issued in Humboldt and Mendocino counties in northwestern California, a region of the state that is relatively undeveloped and until recently, was predominantly covered in natural vegetation (Butsic et al. 2018). This suggests that cannabis cultivation may be concentrated in rural, forested areas where the negative impacts of anthropogenic noise are likely amplified. Empirical data assessing the distribution and impacts of noises resulting from cannabis cultivation, however, are scant. Consequently, in relation to permitted cannabis cultivation in California, we encourage:

• Studies that evaluate the sound output (loudness, frequency, and duration) of cannabis growing operations in rural vs. suburban areas and how sound outputs (a) vary on a daily and annual basis, (b) compare to ambient noise conditions, and (c) compare to the sound outputs of other agricultural practices.

• Studies that assess the effectiveness of varying types of sound attenuation or insulation devices, with the goal of providing recommendations on the best devices/approaches for minimizing sound output to cannabis cultivators.

• Studies that evaluate the level of sound output (specific to cannabis cultivation) necessary to cause take, harassment, or behavioral changes in a variety of threatened and endangered species and how this varies between rural, forested habitats and suburban habitats.

• Studies assessing the call output levels (loudness, frequency, duration) and call response rates of songbirds and raptors in areas with cannabis cultivation vs. (a) areas with no human development and (b) areas with other forms of human development.

• Improving our understanding of the noises associated with cannabis cultivation and how they vary spatially, temporally, and in relation to ambient noise conditions is a critical first step in understanding how these noises may be impacting terrestrial wildlife in California and how they could be better mitigated in the future.

Author Contributions
Conceived and designed the study: LNR, ADB
Collected the data: LNR, ADB
Performed the analysis of the data: LNR, ADB
Authored the manuscript: LNR, ADB, EC
Provided critical revision of the manuscript: ADB, EC

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