Environmental Ethics
Volume 47, Number 4 (Winter 2025): 409–433
DOI: 10.5840/enviroethics202612107

The Mosquito Problem: Evaluating New Mitigation Technologies and Methods

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Several new technologies and methods have been proposed for reducing the incidence of mosquito-borne illnesses. In this article, two new technologies being implemented in the field are examined. A number of criticisms have been levied against these mitigation methods. This paper reviews several salient questions related to animal ethics, arguing although these questions are important, more analysis is needed to answer them. The focus then shifts to two issues yet to be addressed in detail. In short, an analogy can be drawn between an allegory in Aldo Leopold's *A Sand County Almanac* (1949) and possible consequences of these new technologies—specifically, a concern about trophic cascades. There is also a concern the removal of mosquitoes from certain locations might deprive us of an important naturally occurring canary in the global coal mine. If that is the case, then we need to take pause and seriously reconsider these new mitigation methods.

1. INTRODUCTION

An estimated 700 million people contract mosquito-borne illnesses each year, and approximately one million die as a result (CDC 2019). Mosquitoes carry diseases such as dengue fever, West Nile virus, Zika, and Chikungunya, among others. They are by a large margin the deadliest species to humans on Earth (CDC 2019). The yearly medical and economic cost of mosquitoes is in the billions. When we look at these numbers, and when we think about just how annoying and noxious mosquitoes are—at the family BBQ, on a hiking or camping trip, while working outdoors—it becomes tempting to wish all mosquitoes would just suddenly disappear.

In recent years, there have been no lack of efforts to combat these miniature flying vampires. There are now blood packets you can hang on trees to distract mosquitoes from people. There is a new trap made by a company in Mississippi that lures mosquitoes into a tube filled with poison, which they ingest, resulting in their death. But the greatest efforts in the area of mosquito control in the past two decades have come out of big money and the lab. Perhaps the most famous example

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is Bill and Melinda Gates and their foundations' projects. The Gates' foundations are invested in several organizations working on various technologies and methods aimed at tackling the mosquito problem. Since the early 2000s, Bill Gates and the Bill and Melinda Gates Foundation and Gates Philanthropy Partners have invested billions of dollars into these efforts.

In this article, I will look at two technologies and methods currently being considered by the Gates' foundations for addressing the mosquito problem. There are many important ethical questions that can be asked about these proposals. I will primarily focus on two I have yet to see discussed at length in the literature. I will argue 1) there seems to be an analogy between the mosquito problem and an important allegory in US environmentalist Aldo Leopold's 1949 book *A Sand County Almanac*, and 2) these efforts seem to threaten a naturally occurring canary in our global coal mine. I will also spend a bit of time discussing relevant animal rights issues. If it turns out these concerns are warranted, then the mosquito problem, I suggest, is one whose nature is worth seriously reconsidering.

2. PROPOSED SOLUTIONS

The Gates Foundation has funded a number of efforts to reduce the transmission of deadly mosquito-borne diseases. Some of these technologies and methods are at the testing stage. Others are still "in the lab." The first proposal I will look at is an intervention that involves the introduction of a bacterium to a problematic mosquito population. This is the method of Scott O'Neill and the World Mosquito Program (i.e., Technology 1). The second technology I will look at proceeds by introducing genetically modified mosquitoes to a targeted environment. This is the method used by a UK-based company called Oxitec (i.e., Technology 2).

2.1. Technology 1

Let us look first at the mitigation technology of Scott O'Neill and the World Mosquito Program (WMP). The WMP is a not-for-profit group of companies owned by Monash University in Melbourne, Australia and is a grantee partner of both the Bill and Melinda Gates Foundation and Gates Philanthropy Partners. The WMP is doing research on the *Aedes aegypti* mosquito species. This species of mosquito thrives in urban areas, breeding easily on refuse and dirty surfaces. *Aedes aegypti* also prefers biting humans over animals and is more resistant to pesticides. *Aedes aegypti* is the main source of several deadly mosquito-borne diseases, including dengue, Zika, Chikungunya, and yellow fever. The *Aedes aegypti* species of mosquito alone infects upwards of 400 million people each year with dengue fever, with approximately forty million of those infected eventually dying from the disease (CDC 2021). As cities grow and the climate warms and becomes more hospitable for mosquitoes and their reproduction, researchers predict the number of mosquito-borne illnesses and deaths will rise (Dunne 2019, Filho et al. 2019, Colón-González et al. 2021, EPA 2022). And there is already evidence this has been happening (Rocklöv and Dubrow 2020).

To reduce the threat posed by *Aedes aegypti*, the WMP has developed an intervention that involves immunizing mosquitoes of *Aedes aegypti* from the viruses that cause illnesses in humans. How does it work? The key is a bacterium called *Wolbachia*. *Wolbachia* is a bacterium safe for humans and is already found in the cells of many insect species. We consume *Wolbachia* when we eat fruits and vegetables with which some of these insects, e.g., honeybees, butterflies, fruit flies, have interacted. WMP's team introduced a strain of *Wolbachia* from fruit flies into mosquitoes of *Aedes aegypti*. The team found that in mosquitoes with *Wolbachia*, viruses were not able to replicate and therefore were not able to be transmitted to humans.

In mosquitoes, *Wolbachia* is passed down maternally—it is only passed down through eggs, not sperm. If a female mosquito is infected with *Wolbachia* and mates with a similarly *Wolbachia*-infected male, their offspring will inherit the *Wolbachia* bacterium. If a female mosquito infected with *Wolbachia* mates with a male that is not infected with *Wolbachia*, again, their offspring will inherit the *Wolbachia* bacterium. But if a female mosquito is *not* a carrier of *Wolbachia* and a male mosquito *is* and mates with her, then the female mosquito's eggs will not hatch. This is because the sperm of the male mosquito is modified by *Wolbachia* in a way that makes fertilization incompatible (known as cytoplasmic incompatibility) and prevents the mosquito embryos from properly developing (World Mosquito Program 2022).

The long-term result of the method developed by WMP, if implemented on some targeted population of *Aedes aegypti*, and if involving a large enough sample of *Wolbachia*-infected mosquitoes, is mosquitoes with *Wolbachia* eventually become the most established members of the species in that area, in effect breeding disease-transmitting members out. Since *Wolbachia*-infected males that mate with uninfected females result in embryos that fail to develop and *Wolbachia*-infected females that mate with either kind of male result in offspring that carry *Wolbachia*, this gives *Wolbachia*-infected female mosquitoes a reproductive edge. Only their offspring are guaranteed to survive, whereas uninfected females suffer reproductive failure if they mate with infected males. While *Wolbachia*-infected mosquitoes are not "superior" competitors in every biological sense, the reproductive bias introduced by *Wolbachia* gives the infected mosquitoes a spreading advantage, allowing the infection to invade and persist in some targeted population. What is more, the reproductive edge is not one that results in an overall increase in mosquito numbers—rather it results in a replacement or even slight suppression. On the human side of this experiment, the long-term result is a potential reduction in thousands of deaths, millions of serious illnesses, billions in hospital bills, and more.[1]

The number of *Wolbachia*-infected mosquitoes needed to "overwhelm" or replace a native *Aedes aegypti* population depends on several factors, including the number of native mosquitoes and the release frequency of *Wolbachia*-infected

[1] Another group working on this technology is Verily Life Sciences, an arm of Alphabet Inc. devoted to the study of the life sciences.

members. Studies suggest *Wolbachia* must reach a threshold frequency—usually around 30–50 percent of the population—to establish and spread (Hoffmann et al. 2011; Jiggins 2017; Turelli and Barton 2017; Qu et al. 2022). Below this level, the infection dies out simply due to mating odds. To achieve population dominance, WMP focuses on reaching a *Wolbachia* prevalence threshold of at least 60 percent within a targeted mosquito population. To reach the desired threshold, WMP conducts rolling releases over a six- to nine-month period, with a goal of full dominance within twelve months (World Mosquito Program 2016: 27). An effective release ratio (infected to uninfected) often ranges from 5:1 to 10:1 or higher (Beebe et al. 2021). Once enough *Wolbachia*-infected females are present, the *Wolbachia* infection tends to spread and persist without requiring further releases.

2.2. Technology 2

In 2021, a biotech firm funded by Bill Gates released 150,000 genetically modified mosquitoes into the Florida Keys (Oxitec 2021).[2] The group previously had been granted approval to release 750 million such mosquitoes and already had conducted similar tests in Brazil, the Cayman Islands, and Panama (LaMotte 2021). The company since has released more than a million genetically modified mosquitoes in Florida and now has plans for a program in California's Central Valley (Milman 2022). The company, UK-based and US-owned Oxitec, produces genetically engineered male *Aedes aegypti* mosquitoes. This is the same mosquito species on which O'Neill and WMP focus. Only 4 percent of the mosquito population in the Florida Keys is *Aedes aegypti* but this species alone is responsible for all mosquito-borne illnesses in the area (Keys Mosquito Project 2021).

How does Oxitec's intervention compare to that of O'Neill and WMP? Oxitec's plan relies on the fact it is the female mosquitoes of *Aedes aegypti*, not the males, that bite, because females are the ones who need blood to produce their eggs. What Oxitec does is genetically alter male mosquitoes so they now carry a new gene, one such that when a genetically altered male carrier and a wild female mosquito mate, the female offspring produced will not be viable, will not grow old enough to ever bite a human, while male offspring survive and continue the cycle (Osborne 2021). How exactly does it work? It is not entirely clear, but it seems somehow to have do with the newly introduced gene triggering an overproduction of a protein called *tTAV* (tetracycline-repressible transcriptional activator variant). The gene is micro-injected into early mosquito embryos in the lab, typically at the syncytial blastoderm stage (when nuclei divide without full cell division), and includes a female-specific splicing mechanism that ensures only female offspring produce lethal levels of *tTAV*. The injection also contains a fluorescent marker gene (DsRed2), which allows for the identification of modified mosquitoes. The overproduction of *tTAV* wreaks genetic havoc on female mosquito offspring, resulting in those female offspring perishing before they ever reach sexual maturity (Spinner et al. 2022).

[2] In six locations—two on Cudjoe Key, one on Ramrod Key, and three on Vaca Key.

The overall result of the Oxitec method is in the short term, genetically altered male mosquitoes, called OX5034 mosquitoes, that pair with natural *Aedes aegypti* females, produce no viable female offspring (Oxitec n.d.). The long-term result? If enough genetically altered male mosquitoes are released in some targeted area and mate with the local female population, eventually there will not be enough female mosquitoes capable of reproducing for the local species to maintain its existence, and the targeted population will die out. On the human side, the result once again seems to be a reduction in deaths, serious illnesses, hospital bills, and other impacts caused by mosquito-borne diseases—this time with the added benefit of fewer mosquito bites!

Of course, as with Technology 1, the success of a Technology 2 intervention on some targeted population depends on various factors—critically the number of released OX5034 mosquitoes. In field trials, Oxitec has employed high release ratios to successfully overwhelm native populations. For example, in Brazil, release ratios reached up to fifty-four genetically modified mosquitoes for every one non-modified local male (GeneWatch UK 2017). Field trials have revealed dramatic results. In Brazil, targeted mosquito populations were suppressed by 88 percent to 96 percent during peak mosquito seasons (Urquhart 2012).

Unlike Technology 1, Oxitec's genetically engineered mosquitoes are at a reproductive *disadvantage*—they cannot pass on their genes indefinitely. This means the success of Technology 2 requires constant re-releasing of genetically altered mosquitoes to suppress a targeted native population. If releases are stopped, non-genetically altered mosquitoes will theoretically return to dominance over time.

3. REASONS FOR RESTRAINT

There are a number of reasons why one might be concerned about the interventions mentioned here. Indeed, many activists and organizations already have voiced their concerns. Some have suggested such research might be criticized for "playing God" (Pugh 2016). Helen Wallace, executive director of the UK watchdog GeneWatch, discusses gene-altered mosquitoes as examples of "Dr. Frankenstein's monster, plain and simple" (Specter 2012). Others, such as Jaydee Hanson, Policy Director for the International Center for Technology Assessment and Center for Food Safety, have described mosquito gene editing efforts as a sort of "Jurassic Park Experiment" (Center for Food Safety 2020). Others still have worried about factors such as unknown risks and unforeseen consequences (Pugh 2016, Rajagopalan 2022, Wienhues 2022). Some have even argued the eradication of mosquitoes might be wrong for aesthetic reasons, because in a way, mosquitoes are wonders of nature and beautiful in their own right (Hall and Tamir 2022b, Morrison and Lemke 2022). Tina Rulli (2018) provides the most comprehensive summary of responses to such worries.

In this section, I will discuss a few other reasons authors have put forward for worrying about these mosquito mitigation technologies, reasons I have not yet seen discussed at length in the literature and worries that have not, at least publicly, been addressed by the relevant parties.

3.1. Animal Ethics

One issue authors have focused on in the mosquito debate is a concern for animal ethics. Some researchers already have addressed the animal ethics issue in the mosquito case quite thoroughly. Anna Wienhues, for example, considers how such interventions might involve causing harm to sentient creatures or might violate intrinsic rights (Wienhues 2022). And yet, Wienhues ultimately considers these objections overridable. Mosquitoes, she notes, do not seem to feel pain, and it is not clear they are substantially sentient or, in Tom Regan's (2004) words, subjects-of-a-life. For additional support, Wienhues cites Peter Singer's (2016) claim that, regardless of whether insects have sentience, a campaign for insect rights is not yet on the agenda.

And yet, there is now some evidence that members of the order *Diptera*, of which the various mosquito species belong, do meet a significant number of measures for animal pain. Gibbons et al. (2022) applied the eight-criteria framework for assessing pain-related capacities developed by Birch et al. (2021) and found adult *Diptera* met six of the eight criteria with high or very high confidence, indicating strong evidence for the capacity to experience pain.[3] Of course, their evaluation of *Diptera* draws mostly on experimental work done in model species like the common fruit fly (*Drosophila melanogaster*); therefore, more research is needed to fully understand pain perception in mosquitoes in particular. A more recent study by Park and Piermarini (2025), however, suggests mosquitoes detect and behaviorally respond to noxious stimuli via the ion channel protein *TRPA1*, which is thought to be a prerequisite for (though not proof of) pain perception.

Still, evidence of possible pain perception aside, it is not obvious that just because an organism does not feel pain or experience consciousness of some sort that it is not worthy of any further moral consideration—just consider some humans do not feel pain or lack certain aspects of (or lack any) consciousness. The biocentrist tradition in environmental ethics, whose members typically argue for the moral consideration of all life regardless of sentience, is relevant here.[4] Paul Taylor, in his 1986 book *Respect for Nature*, famously argues all living beings have inherent worth and are deserving of moral consideration, not because they are conscious or hold instrumental value to humans, but because they are "teleological centers of life." More recently, Birch (2024) emphasizes caution and ethical responsibility toward beings that might be sentient—are "sentience candidates" in his terms—though, his framework does not extend to entities that in Sebo's (2025) terminology count as "simply alive," such as microbes and plants. Rulli (2018) provides an even more skeptical view of the prospect for an intrinsic value-based defense of mosquitoes.

[3] The six criteria include nociception, centralized processing, motivational trade-offs, flexible self-protective behavior, associative learning, and analgesic behavior. The two criteria not met were self-reporting and analgesic preference.

[4] See Taylor 1986, Callicott 1989, and Varner 1998 for classic biocentrist arguments. More recent positions can be found in Rice III 2016, Birch 2024, and Sebo 2025.

In short, whether mosquitoes are conscious or can feel pain, animal ethics issues are worth taking seriously in this debate. I would like now to highlight a few other ways animal ethics concerns might be relevant to the mosquito problem.

In the case of Technology 1, one issue that has not been discussed at length is the ethics of the act of introducing a bacterium non-voluntarily into another organism. Certainly, the mosquitoes are not in any position to receive information about these interventions or to engage in any form of explicit denial or consent. We cannot ask mosquitoes if they are okay with having bacteria injected into them, and they have no way to signal their preferences on the matter. We take such conditions to be important in human cases. But does a lack of such features in the case of mosquitoes mean this sort of intervention is therefore unproblematic even if it is not harmful or not consciously experienced? Not obviously, especially if animals do have intrinsic bodily rights regardless of their sentience or ability to feel pain.

Some researchers, inspired by human bioethics—particularly pediatric ethics, where children are not assumed to have full autonomy but may nonetheless be granted a "voice" in decisions that affect them—have suggested some animals should be considered as having a voice or at least some form of limited "decisional authority." Fenton (2016) and Fenton and Shriver (2021), for example, worry whether members of some species are able to, among other things, express clear and sustained preferences or aversion through behavior and whether the intervention directly benefits the animal's health or well-being. In the case of Technology 1, these interventions do not seem to directly benefit the health or well-being of mosquitoes. What is more, mosquitoes have been shown to engage in aversive behaviors in other contexts, so there is at least the possibility they might be relevant here.[5]

A similar worry arises for Technology 2: is it morally permissible to genetically modify a species so its offspring will have a genetic disorder that causes them to die prematurely? In the case of Technology 2, the intervention itself is performed on embryos in their early stages. There is no way for the embryos to explicitly signal dissent or behaviorally express aversion. The embryos are also plausibly not conscious or capable of experiencing pain. And yet, the intervention is not of benefit to the health or well-being of the embryos—in fact, quite the opposite for born female mosquitoes.

There is a good question, of course, whether embryos in this situation have the same moral status as born animals. Cochrane (2012) takes up the issue of genetic engineering in animals and argues because embryos lack sentience and the capacity for interests, they do not possess the same moral rights as born members of their species. Genetic modifications at the embryonic stage, Cochrane contends, are not inherently unethical so long as they do not result in the born animals leading lives not worth living. And yet, it seems hard to deny the overproduction of *tTAV*

[5] Kwon et al. (2016) have shown a leucokinin mimetic peptide elicits aversive behaviors in mosquitoes, specifically *Aedes aegypti*, by interfering with the insect's gustatory system. Meyerhof et al. (2025) found *Aedes aegypti* mosquitoes exhibited stronger aversive reactions to rapidly appearing shadows compared to slowly appearing ones. Vinauger et al. (2018) discovered mosquitoes can learn to associate specific odors with aversive experiences, such as being swatted.

in young female mosquitoes (ultimately resulting in their deaths) is not a case of an intervention leading to a life not worth living. What is more, this intervention has effects on later generations of mosquitoes and not just the embryos, and that seems a consideration very much worth weighing.

A different animal ethics worry worth considering is the appropriateness of artificially introducing a modified (and so, no longer "native" in a strict sense) species to some particular environment. Suppose the introduction of modified mosquitoes will not lead to any change in some local environment, and the modified mosquitoes will simply replace local *unmodified* member of the species. In the case where the replaced local species is invasive, this might not seem so problematic—it is in effect an invasive species eradication effort (paradoxically accomplished by introducing another non-native version of the species). But when the replaced local species is *not* invasive—is a native inhabitant—this raises serious questions about the rights native animals have to live and remain in their historical places. Of course, that the introduction of modified mosquitoes will not lead to any change in some local environment is not a warranted assumption, and larger ecological community concerns are worth considering as we will see later in the paper. But whether replacing some native population with an artificially altered one is not morally problematic in its own right is a question well worth contemplating

A third animal ethics worry is more general and partly ecological. In the case of Technology 2, another question that has not been discussed at length is whether it is okay to exterminate a species locally or globally simply because that species makes life harder for us? This is a highly anthropocentric move—one that prioritizes human needs and desires over those of other species and does not treat all species as equal. A move such as this also can possibly have consequences for more than just mosquitoes and humans. We might wonder about the rights of, and the effects on, those non-human animals that eat or otherwise depend on mosquitoes for their continued survival. Janet Fang (2010) argues most animals would get along just fine without mosquitoes, but she acknowledges some species might face decline or even extinction. Her main example is the western mosquitofish (*Gambusia affinis*), a specialized predator so effective at killing mosquitoes that it is often stocked in rice fields as a form of pest control. The loss of these fish potentially could have major consequences for the relevant ecosystems. Fang concludes, however, most species that prey on mosquitoes would be able to adapt and rely on other diets for their survival.

And yet, it is just not clear the removal of mosquitoes would work in the way people like Fang suggest or there would not be unforeseen cascading effects. I will address the ecological side of this issue in more detail later in the paper. But even if things were to go as Fang imagines, it is still not clear 1) this is a fair move with respect to the mosquitoes or 2) depriving other species of a historical food source or of a species that has historically served some other role in the relevant ecosystem, is really a fair move to those animals.

The preceding discussion does not consider mosquitoes are also nuisances or otherwise detrimental for other animals, not just humans. Plausibly, any animal targeted by mosquitoes is not happy (for lack of better words) about these little blood-sucking creatures. In fact, many animals are affected by mosquito-borne illnesses. And so, there is a legitimate species-versus-species conflict to consider here in which one non-human species is causing harm to another. We then face the question of whether humans should intervene to prevent the suffering of one (or more) species in nature by another, especially when we are in a position to alleviate if not entirely suppress that suffering. That is a tough question to answer, and one many authors have tried to address.[6] What counts as the relevant level of suffering for intervention to be permissible (if intervention is in fact permissible)? We certainly do not want to prevent lions from hunting gazelles as they usually do, but it is easy to imagine a scenario where lions might prey on gazelles to an unreasonable extent, likely resulting in negative consequences—not just for the gazelles, but for other species as well, including lions themselves. In short, the animal ethics approach can provide a complicated picture of the overall situation when we think about conflicting rights of animals.

Animal ethics issues have a place in this debate, and many important questions remain unanswered beyond superficial preliminary studies and educated guesswork. We need more careful, targeted empirical research. However, barring that, I would like to focus now on two pressing concerns regarding the mosquito problem—concerns I believe are more immediate than animal ethics issues, especially if we care about human health, which these mosquito interventions claim to improve, and the health of the larger environment, which in turn affects human health.

3.2. A Leopoldian Lesson

In *A Sand County Almanac* (1949), Aldo Leopold tells a story about the day he killed a mother wolf and her pups while he was working as a wilderness ranger in the Southwestern United States. At the time, exterminating large predators like wolves was part of Forest Service policy. The thought was the extermination of wolves and other large predators would make forests safer for humans and cattle and lead to an abundance of deer for hunters. And yet, Leopold writes when he came down from his firing position on a cliff and approached the mortally wounded mother wolf, he saw a "fierce green fire dying in her eyes" and it was at that moment he knew something about the Forest Service's policy of eradication was deeply wrong (130). As Leopold later put it, he realized he had not yet learned to "think like a mountain" (132).[7]

[6] See, e.g., Horta 2017, Johannsen 2020, Faria 2022, Bekoff 2023, Horta and Teran 2023, and Johannsen 2024.

[7] It is worth noting Susan Flader (1974) has tracked Leopold's changing views on the killing of wolves and argued quite convincingly that Leopold likely did not come to this realization until much later in life. It seems, then, the story in "Thinking Like a Mountain" might involve some autobiographical historical revision on Leopold's part.

In the case of the wolves, what Leopold meant by "thinking like a mountain" was he and forest managers had not been thinking about the wolves, the land, the deer, and so on as intimately connected. That is, he had not been thinking enough about the important role that each animal and plant played in what he called the "biotic community" (Leopold 1949: 225).[8]

It turned out government planners were right in a way—killing the wolves did mean more deer, which was good for hunters for a time. But it turned out this was only true in the short term. There were more deer the next season. But there were so many deer that, despite hunters doing their best, the deer population was more than the vegetation in that environment could handle. And so, the next season, there was not enough vegetation for the next generation of deer, and eventually the deer started dying out. In the long term, it turned out removing the wolves had a negative effect on the overall environment.

What Leopold had discovered and described in *Sand County* is now known as a trophic cascade. A trophic cascade is a process by which effects at one trophic level of an ecosystem, e.g., predators, herbivores, or plants, indirectly influence multiple other levels, often in a chain-like reaction that flows through the food web. Since Leopold's discussion, many other cases of trophic cascade have been analyzed—most notable recently is the restoration of a historic trophic cascade in Yellowstone National Park by the reintroduction of grey wolves (*Canis lupus*).

The lesson of trophic cascade is taking out a key species in an ecosystem typically ultimately leads to that ecosystem's destruction. As John Muir once put it, "when we try to pick out anything by itself, we find it hitched to everything else in the Universe" (Muir 1911: 110). The claim I want to make in this article is some of the mosquito mitigation proposals discussed in this paper seem to be vulnerable to similar trophic cascade disruption scenarios. I would now like to discuss my reasons for thinking this is the case.

3.2.1. Technology 1

In the case of Technology 1, I cannot really think of many plausible trophic cascade disruption concerns. Technology 1 simply adds an apparently harmless bacterium to some mosquitoes and then releases those infected mosquitoes into some area where they will eventually out-breed and replace the resident non-immunized mosquito population of the same species. In this case, there is no loss—or very little—of mosquito numbers. That is good for predators and plants that depend on mosquitoes in that area. And so, not obviously worrying in the form of a trophic cascade disruption.

However, one way I can imagine such an intervention possibly leading to a sort of cascade disruption is if the reduced incidence of mosquito-borne illnesses

[8] One might wonder why I do not use the term "ecosystem" here. Roberta Millstein (2018, 2024) has argued Leopold's idea of a biotic community does not map so neatly onto either our contemporary ecosystem concept or our contemporary community concept. Instead, she suggests a blend of those two concepts. I follow her position here.

and deaths of various animal species in some targeted area had some sort of negative downstream effect.

We know many avian species in the United States, e.g., corvids (*Corvidae*), are especially vulnerable to West Nile virus (WNV) and can experience mass die-offs from the disease. One study found by 2005 there was an up to 45 percent decline regionally in populations of the American Crow (*Corvus brachyrhynchos*) and this decline was correlated with the 1999 human WNV epidemic in the United States (LaDeau et al. 2007). Researchers in Stillwater, Oklahoma reported a 72 percent loss in their crow population correlated with WNV in just one year (Caffrey et al. 2005). American Crows face a 100 percent mortality rate when infected with WNV (Yaremych et al. 2004, Kipp et al. 2006, Nemeth et al. 2011). The population of American Crows has started to recover in many parts of the country, but their numbers are still not back to pre-West Nile levels (Kilpatrick and Wheeler 2019).

Although it is possible eliminating or greatly reducing WNV could result in a rise in the population of crows and other avian species, given the other pressures faced by these animals in the form of habitat loss, food availability, and predation, it is not clear the result of a reduction in WNV would be an overpopulation of birds rather than a return to pre-1999 baselines. Of course, we also know corvids are often responsible for nesting failures in other bird species. American Crows compete with other birds—even other corvids—for food and territory. It is worth wondering how a change in the abundance of crows and other birds might impact these conditions as well as factors like seed dispersal, insect numbers (and their effects on plant life), and rodent populations (and their relation to increases in other diseases).[9] In short, an increase in the American Crow population has the theoretical potential for negative cascading effects, though it seems unlikely. Future research is needed to determine just how probable such effects really are.

In the case of non-human mammals, certain primates, e.g., howler monkeys (*Alouatta*), are known to be highly susceptible to yellow fever. Between 2016 and 2018, the yellow fever outbreak in southeastern Brazil had a devastating impact on local howler monkey populations (Dietz et al. 2019). One study suggests in black and brown howler monkeys (*Alouatta caraya* and *A. guariba*, respectively) mortality rates range from 20–90 percent (Moreno et al. 2015). In El Piñalito Provincial Park in Argentina, a systematic survey of local howler monkey populations noted a significant number of dead howler monkeys. In some cases, populations were so affected there were reports of local extinctions (Holzmann et al. 2010).

In the case of howler monkeys, it is not clear the elimination or significant reduction of yellow fever would in turn result in an overpopulation of this species and so some sort of disruption of the local trophic cascade. Howler monkeys and many other primate species face significant pressures, e.g., rising habitat loss, reduced food availability, and increased predation. Howler monkeys also contend with low reproductive rates—females typically give birth only once every one to

[9] See Levi et al. 2012 for a study linking reductions of small-mammal predators to an increase in the risk of Lyme disease.

two years (Glander 1980, Strier et al. 2001). Additionally, many howler monkey species are also at or near historic population lows. The black howler monkey, for example, is listed as Near Threatened by the International Union for Conservation of Nature (Marinho-Filho and de Oliveira 2021a). The northern brown howler (*Alouatta guariba guariba*) is critically endangered with fewer than 250 individuals remaining in the wild (Marinho-Filho and de Oliveira 2021b). Thus, a reduction in the deaths of howler monkeys seems unlikely to result in an overpopulation crisis.

In the case of humans, on the other hand, our overpopulation is, of course, already a sad reality. Yet ideally that is a problem that would be addressed by means other than maintaining (as opposed to decreasing) current rates of mosquito-borne illnesses.

3.2.2. Technology 2

Technology 2 has significant room for worries about the disruption of trophic cascades. As mentioned earlier, Fang (2010) suggests most animals and plants would get along just fine without mosquitoes. And yet, it is worth emphasizing that most is not all. A 2017 workshop report in the *American Journal of Tropical Medicine and Hygiene* by Roberts et al. suggests at least in sub-Saharan Africa, the elimination of *Anopheles gambiae* mosquitoes likely would have no negative ecological effects, but the authors also note some spider species are known to prefer anophelines (Jackson et al. 2005). I already have mentioned earlier the possible effects on mosquitofish. Bruce Harrison, an entomologist with the North Carolina Department of Environment and Natural Resources, has estimated that eliminating mosquitoes from the Artic tundra could potentially cut the population of migrating birds that nest there—and who feast on mosquitoes in these otherwise food scare regions—by greater than 50 percent (Fang 2010: 432).

There is also room for worry about the direct effect of mosquito elimination on plant life. Research has shown that the blunt-leaved orchid (*Platanthera obtusata*), which is native to northern North America and parts of Eurasia, is primarily pollinated by Aedes mosquitoes (Gorham 1976, Lahondère et al. 2019). These plants have evolved to produce a compound called nonanal, which mimics human and animal odors and acts as an attractant to mosquitoes. Mosquitoes are the main pollinators of this species, though other insects such as moths also take up a small role. If mosquitoes were removed, the blunt-leaved orchid's population could diminish or face local extinctions, affecting not only the orchids but also other organisms that rely on them. Other plant species such as *Burmannia lutescens*, *Gnetum cuspidatum*, and *Sciaphila* spp. have been documented to be pollinated exclusively by certain mosquito species (Kato 1996).

That it is actually true the elimination of mosquitoes would not have negative cascading effects on ecosystems is still an uncertainty. If we start eliminating populations of mosquitoes—especially if we go global, as I mentioned earlier—it is possible we have a negative effect on those animals, and even plants, that depend on mosquitoes, which in turn would affect those animals and plants that depend on those other animals and plants for their survival, etc.—a disruption of a trophic cascade.

A trophic cascade disruption also could occur if, for example, the eradication of mosquitoes, and not just the human-harming viruses they carry, resulted in an increase of other species. Hall and Tamïr (2022b) point out mosquitoes transmit microbes to bats, helping to control bat populations and, in turn, reducing the spread of diseases harmful to humans (e.g., rabies, histoplasmosis, Nipah virus, and SARS-CoV). Roux and Robert (2019) note certain mosquito species (members of the genus *Toxorhynchites*) prey on the larva of other mosquito species, in effect controlling their populations.

Fortunately, all Technology 2 proposals so far have been rather narrow in scope. And yet, as other researchers have noted, there is still another way these sorts of trophic cascade disrupting worries could play out, namely if it is possible for some genetically altered mosquitoes to escape a targeted area and start working their magic in other places (Wise and Borry 2022) or if they interbreed with other mosquito species (Rulli 2018). These sorts of situations could snowball and lead eventually to larger trophic cascade disruptions.

3.2.2.a. Lesson from the Dinkey Lakes

I now would like to shift focus and style briefly and consider another potential hazard of Technology 2. One summer I worked as a Wilderness Ranger in the Sierra National Forest in the Sierra Nevada mountains of California. Sometimes the crew I was in would work in the Dinkey Lakes Wilderness. The Dinkey is one of the most beautiful wildernesses in the Sierra, in my opinion. People often balk at that statement. More beautiful than the John Muir Wilderness? Prettier than the Ansel Adams Wilderness? Yes, in some parts and in some ways.

The Dinkey, of all the wildernesses in the Sierra National Forest, which also includes the John Muir, the Ansel Adams, and the Kaiser, is arguably the least visited and in some ways the "wildest." I would wager it is also one of the least-visited wilderness areas in all the range. Some of this likely has to do with the Dinkey's placement and name. The Dinkey is close to the Ansel Adams, the Muir, Yosemite National Park, and Sequoia-Kings Canyon National Park—most people do not have the time to visit them all and just hit the most famous locations. As far as the name goes, Dinkey Lakes just is not the most awe-inspiring of titles, and it has no famous personality attached to it. In many ways, without knowing the story of the Dinkey, it sounds like the name means the wilderness is just filled with a bunch of "dinkey" lakes.[10]

But the Dinkey Lakes wilderness is a special place. It is not as high up as the John Muir or the Ansel Adams. There are lots of meadows, wildflowers, butterflies, lodgepole pines (*Pinus contorta*), white firs (*Abies concolor*), and mountain hemlock trees (*Tsuga mertensiana*). Dogtooth Peak stands in the middle and can be climbed if you have the gusto. There are also many little creeks flowing through the Dinkey, and, yes, many little lakes.

[10] The origin of the name of the wilderness is disputed, but the story handed down to me is of an old prospector who ran into a bear in the area and was saved by his faithful canine named Dinkey.

One of the best parts of the Dinkey, however, is the lack of people that visit the area; the opportunity for solitude. Another is the abundance of wildlife. In the Muir and the Ansel, people are everywhere, and animal sightings are scarce. Of course, there are still some places to find solitude and good opportunities for animal viewing in those wildernesses, way high up and off the beaten path. But due to the Pacific Crest Trail and the John Muir Trail, and word of mouth and now Instagram, these places often have someone hiking or camping in just about every part of them almost every night of the summer—a real pain for rangers who now must check permits to keep a check on visitor numbers and a pain for visitors hoping to experience a day or night alone in nature. In the Dinkey Lakes, on the other hand, everything is quiet. You hear yourself, the land, the weather. You see the animals. It makes one wonder: what is it that makes the Dinkey so different?

The answer is in part that the Dinkey is also the only part of the Sierra wilderness to routinely get overrun by mosquitoes for most of the summer. Never in my life have I seen mosquito plumes so thick, and I have lived in Mississippi! As a backpacker, it was the first and only time I have ever needed to wear a mosquito net over my head the entirety of the five days we were on patrol. Even while I ate, I would keep the net on and put my spoon under the netting. When in the Dinkey, even experienced rangers keep their mosquito nets on at all times, give up swimming in the lake after work, and uncharacteristically retire early to their tents. I have never been bitten so many times or looked up to see so many mosquitoes on a crew member's back. It was a constant battle.

But one day, while hiking through the onslaught of these little vampire fairies and wishing that all mosquitoes were dead, I had an epiphany. We came to a beautiful view of an alpine lake, and seeing that no one was there, that it was so quiet and all ours, near pristine—something nearly impossible to find in the Muir or Ansel—it dawned on me. The mosquitoes functioned as sort of unintentional little guardians of these places. Those parts of the world with native mosquito populations have tended to keep their biotic communities more intact, their wildernesses more undisturbed, because people do not want to deal with going in and getting bitten. Since that day, I have gained a greater appreciation for mosquitoes. These creatures that seemed to serve no real deep purpose other than to kill and cause pain, turned out to serve a purpose more important than most realize. Without mosquitoes, the Dinkey, despite its name and location, would very likely have fared much worse over the years in terms of disturbance and overuse by human visitors. All rangers know visitors plan their trips in part on when and where the mosquitoes are not biting. Get rid of the mosquitoes and visitation goes up. Without the mosquitoes, the Dinkey would have lost much of what gives it its wilderness character and faced a greater disruption of its biotic community. The same is likely true of other wild places.

Marcus Hall and Dana Tamïr (2022b) anticipate this worry to some extent when they write "Metric tons of flying biomass certainly alter natural processes, whether as foodstuff for other organisms or as modifiers of animal behaviour, as in the case of caribou and *Homo sapiens* who move or migrate to avoid them" (6).

As Fang (2010) acknowledges, mosquitoes are such pests to caribou it is thought caribou herds travel facing into the wind in an effort to escape mosquito swarms. Even a slight alteration in the migratory patterns of large mammal herds can have significant consequences for the areas through which they migrate.

To put it succinctly, if we get rid of mosquitoes in some areas, as Technology 2 seems to entail, there is the real possibility of inducing a disruption of various ecosystems in this more indirect way—by making some areas that are currently wild more hospitable to humans or other animals, who will then increase how much they use or occupy those areas and so impact the local flora and fauna—trampling plants, driving away wildlife, overusing resources, etc., in effect degrading those wild spaces. In some ways, this ties back into worries about animal ethics. Is it okay for us to scare away the animals with our presence in this way and to reduce the life-giving flora of that ecosystem? It also comes back to more general trophic cascade and health worries. If we do this enough, we will degrade the larger environment, a move that in effect comes back to bite us humans—pun intended. Of course, there are ways this sort of problem could be mitigated without maintaining mosquito populations. Limits on the number of visitors permitted in these areas could be implemented, for example. But this is not a solution that will work for all wild places, especially those under less governmental control, and it assumes those places under strong governmental control will have the political will and resources to implement such restrictions—and even here in the wealthiest of nations, the U.S. Forest Service and National Park Service face historically low levels of funding and staffing.[11]

In a way there is a two-part concern worth considering here. Not only might the increased use of an area by humans disrupt the biotic community, but the other side of the coin is the concomitant loss of that area's wilderness character, e.g., its degree of solitude, its natural untrammeled beauty, its sights, sounds, and smells. Wilderness character is deeply connected to the unaltered flow of an ecosystem and is something rangers, organizations like the National Park Service and U.S. Forest Service, and other authors have advocated for the protection of in detail (Abbey 1968, Cole 2006, Landres et al. 2008, Kaye 2015). The elimination of mosquitoes has the potential to leave a marked negative impact on an area's wilderness character and not just its local trophic cascades. In fact, it seems almost impossible that certain mitigation efforts would not have such an impact.

3.3. The Canary in the Coal Mine and the Mosquitoes in the Mountains

In this section, I will discuss one last possible worry about recent mosquito interventions, one that also ties back into more general concerns about human health and the health of the environment.

[11] I am told in the Sierra National Forest, for example, there used to be about ten full-time wilderness rangers assigned to each wilderness area, whereas nowadays that number has dropped to about one ranger and, if lucky, a few seasonal volunteers.

Sometime later in my Forest Service career, I was working for the Inyo National Forest on the eastern side of the Sierra as an apprentice horse and mule packer on a forest fire. 2020 was to become the worst forest fire season in California history. Fires seemed to be everywhere. Everyone was being called up, units not just from California and neighboring states but from as far as Alaska, Montana, even outside agencies from Mexico. The government even brought in prisoners to boost the number of boots on the ground.[12] One of my old supervisors from the Sierra National Forest met up with my unit to help us out. I asked her how things were over on the western side of the mountain. She reported to me it was the driest summer season she had ever experienced. She had worked on the Sierra for forty years. And she said this was the first time in her life she had not seen a single mosquito in the Dinkey Lakes Wilderness.

For all of us who have worked in the Dinkey, the idea there ever would be a summer without mosquitoes there was a shocking prospect and until then impossible to imagine. It was a revelation that made many of us go into deep reflection, realizing the disappearance of the mosquitoes was almost certainly a sign of some more fundamental disturbance in the way of nature. For me and my supervisor, it became obvious the mosquitoes in the Dinkey were a sort of canary in the coal mine. The disappearance of the mosquitoes in a place like the Dinkey meant it was far too dry there, so dry the coming forest fire season was almost certain to be horrific. The disappearance of the mosquitoes in the Dinkey served to tell us that in the Sierra, climate change, severe drought, or some other cause was having its effect.[13] If we eradicate mosquito populations in places like the Dinkey, we lose an important natural gauge—one that reliably reflects changes in global warming, drought, and other environmental conditions, and serves as a difficult, if not impossible, to replace canary in the coal mine for impending severe wildfire seasons.

This might seem like an odd reason to care about mosquitoes, as sort of bioindicators of drought and wildfire risk. However, other species have been used in just this sort of way for other purposes. Because of their extreme sensitivity to WNV, American Crows can serve as a key sentinel species for public health agencies interested in monitoring for the presence of WNV and the risk for potential outbreaks in local human populations (Mostashari et al. 2003, Eidson et al. 2005, Johnson et al. 2006). Moreover, caddisflies have been used to assess water quality and stream integrity (Pereira et al. 2012, Thamsenanupap et al. 2021).

[12] A policy that warrants ethical scrutiny in its own right.

[13] I hesitate to put all the blame on climate change here, though it does seem to me to be a reasonable suspect. Unfortunately, the data just are not conclusive in this case, as there is simply not enough scientific information on the annual variance of mosquito populations in this part of the Sierra. The best information we have is the observations of career rangers like that detailed above—still important, however, as there is a genuine gap in the scientific knowledge here. This issue might remind readers of the weather attribution problem: when can an extreme weather phenomenon be explained in terms of climate change rather than some other local factor? Analogously, we can ask when is the non-appearance of mosquito populations best explained by climate change rather than some other cause(s)?

Of course, there are other ways to predict and measure wildfire risk. But preventing wildfires requires identifying areas of risk as early as possible. Ideally, risk indicators should, among other things, be relatively inexpensive, easy to deploy, and capable of providing timely and accurate forecasts. More studies should be conducted. However, mosquito population reports may offer several advantages: 1) mosquito populations appear to be highly sensitive to drought, which makes local extreme drought conditions relatively easy to detect, 2) mosquitoes are widely distributed, and their density is generally easy to recognize, and 3) conducting mosquito population surveys requires very few resources and little time.

4. DISCUSSION

The lessons to be drawn from this paper are fairly simple. We looked at two bio-technological methods proposed for reducing mosquito-borne illnesses and deaths. Both methods have various worries worth contemplating. However, one of those methods, Technology 2, seems to have significant potential for trophic cascade disruption and the elimination of an important canary in the global coal mine. At this point, one might wonder if this means we should at the least not engage in Technology 2-style reduction methods. Answering that question, however, is outside the scope of this paper. Rather, this article is meant to encourage a precautionary approach to the implementation of future bio-technological interventions and to light a lamp on these recent developments.

As mentioned earlier, if one of our worries about Technology 2 implementations is an increase in human occupation in targeted areas, there might be mitigating strategies available that can make up for such interventions, e.g., tighter limits on and enforcement of hiking and camping permits, on development or resource use, etc. The worry that genetically altered mosquitoes might leak to other populations, or this technology might be used globally, on the other hand, is a trickier matter. It is just not clear how tracking and prevention could be accomplished to prevent leaks from targeted areas into others. No such proposals have been put forward. And in the case of worries about more global implementation, it is just not clear there is a good move presently available other than to simply try not to let it happen.

There are, of course, other, no less concerning, worries about these interventions, worries I have not discussed at length in this paper. For example, there are concerns from an indigenous and non-Western perspective. Some communities might worry reduction efforts will be used to facilitate the colonization and development of their lands. Or they might worry these efforts involve a sort of colonial paternalism (Rajagopalan 2022). Others, still, might, from the other direction, complain those who call for halting mitigation projects are choosing nature over the health of people. And then we might also wonder whether promoting certain interventions is, in fact, a way to avoid implementing others—those that would be more just and equitable, improve the living conditions of less well-off communities, but also prove costlier or require sacrificing aspects of our modern Western way of life (Stepan 2022: 83, Willott 2002).

It is important to identify a full range of concerns when adopting a precautionary approach toward future bio-technological interventions. Such caution offers, I believe, our safest path forward, ensuring innovation proceeds without neglecting potential risks. This paper serves to advance that ongoing effort, and I hope it will be one of many contributions to a future in which technological progress never outpaces our ethical responsibility.

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