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The Unintended Ecological and Social Impacts of Food Safety Regulations in California's Central Coast Region

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In 2006, a multistate Escherichia coli *O157:H7 outbreak linked to spinach grown in California's Central Coast region caused public concerns, catalyzing far-reaching reforms in vegetable production. Industry and government pressured growers to adopt costly new measures to improve food safety, many of which targeted wildlife as a disease vector. In response, many growers fenced fields, lined field edges with wildlife traps and poison, and removed remaining adjacent habitat. Although the efficacy of these and other practices for mitigating pathogen risk have not been thoroughly evaluated, their widespread adoption has substantial consequences for rural livelihoods, biodiversity, and ecological processes. Today, as federal regulators are poised to set mandatory standards for on-farm food safety throughout the United States, major gaps persist in understanding the relationships between farming systems and food safety. Addressing food-safety knowledge gaps and developing effective farming practices are crucial for co-managing agriculture for food production, conservation, and human health.*

Keywords: agroecosystems, conservation, public health, Escherichia coli *O157:H7, pathogen, socioecological system*

An *Escherichia coli* 0157:H7 outbreak in spinach in 2006 sickened hundreds and triggered systemwide reforms to the leafy greens industry (LGMA 2013). Farming practices for fresh produce in California's Central Coast region (figure 1a), where the outbreak originated, changed markedly in response, leading to a variety of unintended social and ecological impacts. Concern that wildlife vectored the disease led to strong pressure on growers to erect fences, set out wildlife traps and poison, and remove vegetation that might harbor wildlife around their farms. Growers bore the cost not only for preventing wildlife intrusion but also for monitoring contamination, funding self-audits, maintaining records, hiring food-safety staff, and forfeiting suspect crops. Research to date has documented the socioecological changes generated by the food-safety reforms in the Central Coast region (Beretti and Stuart 2007, Lowell et al. 2010, Gennet et al. 2013), which can provide insight into what may happen if similar reforms are adopted on farms throughout the United States.

Preventing life-threatening illness is a clear public-health priority. Our purpose in discussing the socioecological impacts of on-farm practices for food safety is to advance the conversation on the need for and opportunity to co-manage agricultural, environmental, and public-health objectives in an integrated framework. Here, we briefly discuss the development of US food-safety policy to contextualize how industry, government, and the American public responded to the 2006 *E. coli* O157:H7 outbreak. We then review how and why agricultural practices have changed in the Central Coast region and identify potential externalities of produce-safety reform that deserve further scrutiny. On the basis of insights gained from the Central Coast, we then illustrate more generally how foodborne outbreaks can reverberate through socioecological systems. Finally, we suggest a path forward to close important knowledge gaps and move toward an agricultural system that is co-managed for multiple benefits, including food safety; agricultural production of fresh, nutritious food; nature conservation; and ecosystem services.

Context for the response to the 2006 *E. coli* 0157:H7 outbreak

Although 2006 marked a turning point for produce-safety reform, produce-related illnesses have been increasing for

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some time, from 1% of foodborne diseases in the 1970s to 12% in the 1990s (Lynch et al. 2009). Recent estimates suggest that fresh produce is now the leading cause of foodborne illness in the United States: From 1998 to 2008, fresh produce accounted for 46%, 38%, and 23% of foodborne illnesses, hospitalizations, and deaths, respectively (Painter et al. 2013).

Several hypotheses exist for this increase: First, a rapid growth in confined animal feedlots since the 1980s may have increased foodborne-disease prevalence, which can then cross-contaminate produce fields through water, manure, or wildlife (Kellog et al. 2000, Franz and van Bruggen 2008, Lynch et al. 2009). One study in the Midwestern United States reported that approximately 10% of the feedlot cattle in approximately 50% of the pens shed *E. coli* O157:H7 (Callaway et al. 2006). Second, Americans are eating more produce, increasing overall exposure (Lynch et al. 2009). Third, new in-field cutting and coring technologies may make plants more vulnerable to contamination (Lynch et al. 2009). Finally, globalized food networks, centralized packing and processing facilities that mix food from many sources, and the introduction of premixed and cut produce increase the likelihood and magnitude of pathogen spread (DeLind and Howard 2008, Stuart and Worosz 2012).

This complexity confronts a US food-safety system that has "developed in fits and starts as the nation's attention turned to one crisis after another" (FSWG 2009). The 2006 outbreak marked yet another iteration in a century-long cycle of crisis and reform that began with Upton Sinclair's famous 1906 exposé on the meat-packing industry, *The Jungle*. The ubiquitous negligence and unsanitary conditions exposed by Sinclair sparked public outrage that led to the rapid passage of the Pure Food and Drugs Act and the Meat Inspection Act of 1906. These laws split federal oversight such that the US Department of Agriculture (USDA) regulates meat products whereas the Food and Drug Administration (FDA) oversees drugs, cosmetics, and all other foods.

This divide shapes produce-safety reforms today. Among the FDA's many missions, regulating microbial pathogens on food has not necessarily been a top priority (Nestle 2003). Although the FDA is responsible for regulating 80%–90% of the nation's food, the agency's FY 2014 food safety budget of $882 million lags behind that of the USDA, set at $1 billion (Johnson 2014). Furthermore, in FY 2006–2007, the FDA spent only 3% of its food-safety budget on fresh produce, despite acknowledging fresh produce as a priority since 1997 (GAO 2008). Constrained by budgetary and staff limitations and facing a continually expanding food system in which potential contamination routes multiply and become harder to control, the FDA cannot set, monitor, and enforce produce-safety standards on its own. As a result, the private sector plays a growing role (Fuchs and Kalfagianni 2010, Bain et al. 2013). Many supermarkets and foodservice firms now set their own standards for safe food production above and beyond government rules and recommendations, relying on third-party auditors to verify farm compliance.

Nonetheless, recent polls report that 73% of surveyed American consumers ($N = 2236$) still believe that the government should have more oversight of food safety (Harris Poll 2014). In response, the FDA has turned toward a coregulatory approach for produce safety (Garcia Martinez et al. 2007). This is facilitated by a cooperative management model developed in the 1970s in collaboration with the food-processing and drug-manufacturing industries. Under this model, known as *hazard analysis and critical control points* (HACCP), each firm is responsible for identifying all hazard sources in its production process and setting control targets to prevent contamination. The FDA has the power to inspect firms and verify that they are following their HACCP plans, but in practice, firms enjoy "substantial latitude," as was described by Coglianese and Lazer (2003).

Although HACCP systems are now near universal in many latter stages of the supply chain, farm fields pose unique challenges for full implementation because they are neither closed nor linear systems. Therefore, the FDA, in collaboration with industry, generalized HACCP principles to develop guidance on good agricultural practices (GAPs), now the baseline for produce-safety standards. However, the underlying tension inherent in applying food-safety principles developed for the controlled industrial context of factories to the dynamic ecological matrix of farm fields remains unresolved (Stuart 2008).

In short, regulating produce safety in the United States is a complex task split between industry and government agencies and informed by past public health crises located far from the farm field. After high-profile outbreaks, underlying tensions over fragmented roles and responsibilities can flare to precipitate rapid reforms that prioritize acutely perceived risks (DeLind and Howard 2008). Below, we outline how these reforms took shape in the California Central Coast region.

The 2006 *E. coli* 0157:H7 outbreak

In 2006, a 26-state outbreak of *E. coli* O157:H7 transmitted through bagged spinach killed 3 people and sickened approximately 200 (Centers for Disease Control 2006). Consumers avoided spinach for months, costing the leafy-greens industry $350 million in lost sales (Weise and Schmit 2007). The pathogen source was traced to a farm in the California Central Coast region, where the infecting strain was detected in the farm environment, feral pigs, cattle feces, and the local watershed (CDHS-FDA 2007, Cooley et al. 2007). This discovery launched a wave of reforms that intensified food-safety regulation of the farm field.

California produces most of the nation's leafy greens, accounting for 71%–85% of lettuces, 60% of fresh spinach, and 85% of processing spinach harvested in 2012 (CDFA 2014). Given that leafy greens are now estimated to be a leading cause of foodborne disease (Painter et al. 2013), this economic position has put California growers at the vanguard of produce-safety reform. After 2006, media coverage and consumer concern pressured producers, food retailers, and the federal government to strengthen controls over pathogens in produce. These stakeholders drafted the California Leafy Greens Marketing Agreement (LGMA) to set and ensure compliance with best practices for produce safety (LGMA 2013). By volume, 99% of California leafy greens are now LGMA certified. The LGMA is another very recent example of a quasipublic regulatory arrangement: Although participation is voluntary, state government officials enforce compliance once growers sign on. Growers selling to large retail and foodservice companies must often meet additional requirements, known as "supermetrics" (Endres and Johnson 2011), set by these buyers. Proprietary "supermetrics" are rarely publicly disclosed, and little concrete information is available on how they differ from public standards.

In 2010, the federal government passed the Food Safety Modernization Act (FSMA). The FSMA expands the FDA's mission to prevent pathogen contamination early in the supply chain, extending its oversight to farm-level production. The agency's final produce-safety rule, still in draft form as of the writing of this article, will regulate the production and trade of many fresh fruits and vegetables (supplemental table S1), potentially affecting agricultural practices throughout the United States and countries that grow produce for US markets (Paggi et al. 2013).

Requirements and practices

Each of the recent food-safety reform initiatives—the LGMA, private-sector requirements, and the FSMA produce-safety rule—look to the FDA's 1998 GAPs guidance to provide a framework for how pathogens should be controlled on the farm (FDA 1998). Although many microbiological hazards, including *E. coli* O157:H7 and *Salmonella*, are vectored by livestock and wildlife (Franz and van Bruggen 2008), pathogens can also spread through soil, water, workers, and farm equipment, in addition to cross-contamination during processing or distribution. In the case of the LGMA, risk-management approaches target on-farm sources, which has led in some instances to major changes in farming practices (LGMA 2013).

Compliance with produce-safety standards also means satisfying the expectations of external inspectors and auditors (Thompson LJ and Lockie 2013), who tend to adopt a universal "expert model" for best practices that does not necessarily incorporate farmers' site-specific understanding of the food-safety risks on their farms (Parker et al. 2012). Compliance with formalized audit systems can pressure growers to standardize farm management despite socioecological differences between sites and across scales (McMahon 2013).

Irrigation and floodwaters. Many pathogens can spread through water (Pachepsky et al. 2011), and intense rains and subsequent runoff may thus transport pathogenic *E. coli* from upstream contamination sources (e.g., urban sites, pastures, or feedlots) to streams in produce-growing regions (Cooley et al. 2007). Flooding and/or irrigation can distribute pathogens from these waterways across fields, elevating food-safety risks.

Irrigation waters have been linked to disease outbreaks in multiple countries and crops (Pachepsky et al. 2011). To mitigate risks, the LGMA requires growers to maintain specific microbiological criteria for irrigation water by conducting monthly tests (LGMA 2013). If a water sample exceeds maximum allowable microbial counts, growers must stop using that water until conditions improve. Treatment options include fencing waterways to prevent animal defecation in rivers, chlorinating the water, and constructing waste stabilization ponds or storage reservoirs (Pachepsky et al. 2011). The LGMA also regulates practices related to floodwaters. No harvesting is allowed within 30 feet of flooded areas, and no subsequent planting can occur for at least 60 days (LGMA 2013). However, "supermetrics" can greatly exceed LGMA recommendations: One company mandated a 5-year waiting period before buying crops produced on flooded lands (Lowell et al. 2010).

Soil amendments. Applications of manure and animal-based composts may pose a food-safety risk. Several *E. coli* O157:H7 outbreaks have been associated with direct human contact with animal manure (Ferens and Hovde 2011), but proper composting can reduce risk. For example, *E. coli* O157:H7 could not be detected in manure after two weeks of exposure to 50 degrees Celsius (°C), a temperature regularly exceeded inside compost windrows but not on the windrow surface (Jiang et al. 2003). To ensure that compost is properly treated, the LGMA (2013) recommends that compost windrows attain internal temperatures of at least 55°C for 15 days and be turned over at least five times so that no particles on the windrow surface avoid heat treatment. The LGMA also bans raw manures and compost with any animal manure beginning 45 days before harvest. Since the 2006 outbreak, raw manures have now all but disappeared in California's Central Coast. In addition, growers have scaled back compost applications in favor of physically heat-treated soil amendments or fertilizers that do not contain animal products (Lowell et al. 2010).

Contact with animals. Livestock, pets, and wildlife can vector pathogens, and minimizing their intrusion into crop fields has become another focus of food-safety regulation (Ferens and Hovde 2011). Reported wildlife intrusion was a significant risk factor for a *Listeria* contamination of farm fields in New York (Strawn et al. 2013). Several outbreaks have been associated with animal intrusion, including the 2006 spinach outbreak after the disease-causing strain was detected in nearby cattle and feral pigs. However, the strain was also detected in adjacent waterways and throughout the farm environment, leading an official traceback report to reveal that "no definitive determination could be made regarding how *E. coli* O157:H7 pathogens contaminated spinach in this outbreak" (CDHS-FDA 2007).

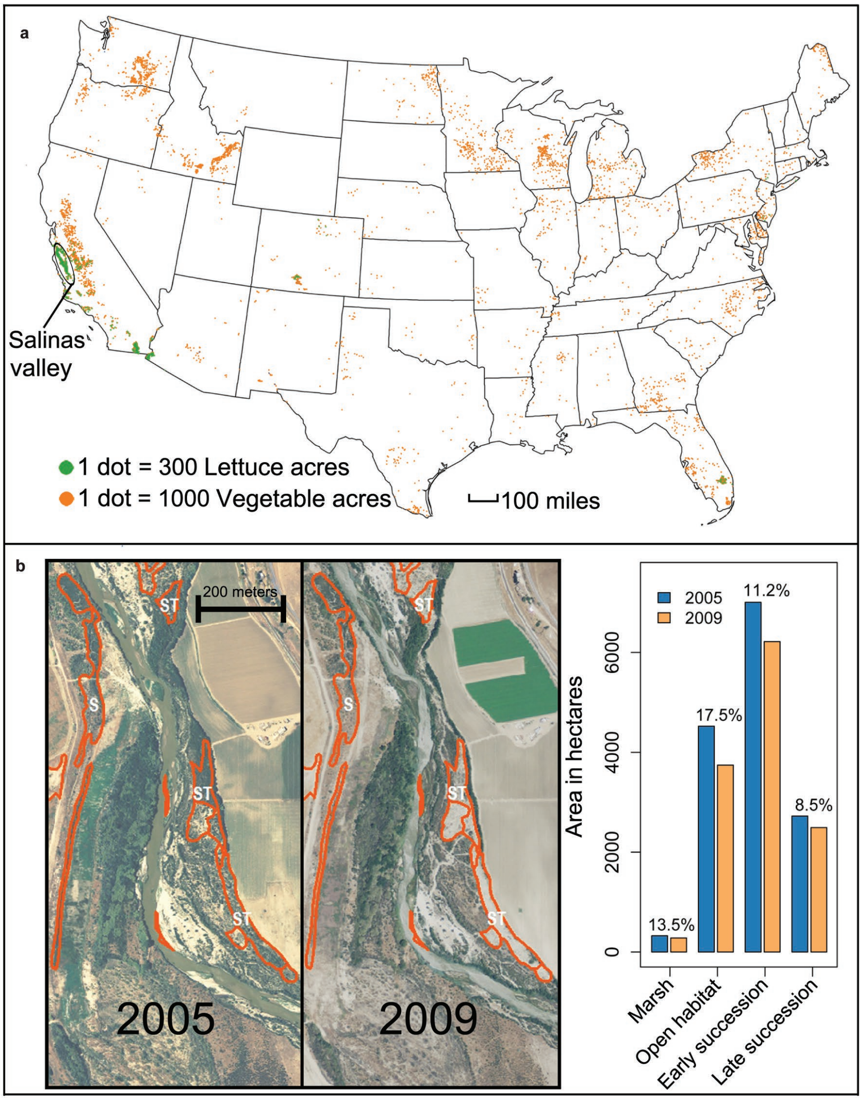


Figure 1. A map of the study region and documentation of food safety–induced habitat removal. Panel (a) depicts major vegetable and lettuce growing regions in the United States, on the basis of the 2007 Census of Agriculture conducted by the US Department of Agriculture. Most of the lettuce produced in the United States originates from the California Central Coast. Panel (b) illustrates food safety–induced vegetation removal. The left images illustrate the areas of decline (orange polygons) in shrub and tree cover (ST) and shrub cover (S) along the Salinas River. The right graph depicts the aggregate area (hectares) of natural habitat types prior to (2005) and following (2009) the **E. coli** *O157:H7 outbreak. Numbers are percent declines. Figure adapted from Gennet and colleagues (2013).*

The prevalence of pathogens in wildlife is often lower than in cattle, depending on the pathogen. For example, one study in the California Central Coast region reported pathogenic *E. coli* in 37.9% and 7.4% of cattle and wildlife samples, respectively (Cooley et al. 2013). For infected wildlife to contaminate produce to a sufficient degree to cause illnesses, infected animals must not only carry pathogens but also enter fields and deposit contaminated feces. The LGMA guidelines for animal intrusion have evolved from a focus on "animals of significant risk" (deer, pigs, cattle, sheep, and goats) to a general requirement to monitor signs of intrusion by any animal (e.g., tracks, damaged plants, and feces). The LGMA advocates for 5-foot no-harvest buffers if feces are found (LGMA 2013), but some buyers require larger buffers. One incident of deer intrusion into a field along the Salinas River caused a farmer to lose 10 acres of crop (Lowell et al. 2010).

Conflicts with conservation. Despite the lower apparent risk profile of some wildlife compared with that of livestock, growers report yielding to strong pressure from buyers to prevent wildlife intrusion (Beretti and Stuart 2007, Stuart 2009, Lowell et al. 2010). A survey of 181 Central Coast farmers found that 15% had discontinued conservation practices restoring wildlife habitat, whereas 89% had adopted measures such as erecting fences, wildlife traps, or bare-ground buffers to discourage wildlife intrusion (Beretti and Stuart 2007). Interviews have revealed that removing noncrop vegetation or eliminating wildlife posed an ethical dilemma for over one-third of interviewed growers, who felt they had to choose between conflicting regulatory and environmental expectations (Stuart 2009).

In an interview of 154 growers, 47% reported being told by auditors or other industry or LGMA inspectors that wildlife is a big food-safety risk (Lowell et al. 2010). From 2005 to 2009, growers removed approximately 13% of the remaining riparian habitat in the Salinas Valley of California's Central Coast (figure 1b; supplemental table S2), replacing it with lower-stature vegetation or bare-ground buffers designed to reduce animal movement and allow for better wildlife monitoring (Gennet et al. 2013). Buffers between produce fields and areas of perceived risk (e.g., roads, forest, or water) significantly mitigated the *Salmonella* and *Listeria* prevalence on farm fields in New York (Strawn et al. 2013). Recent evidence, however, suggests that clearing vegetation to create bare-ground buffers may not be effective at reducing pathogen prevalence. Analyzing more than 250,000 tests for pathogenic *E. coli*, indicator *E. coli*, and *Salmonella* in fresh produce, water, and rodents, Karp and colleagues (2015) found no evidence of elevated pathogen levels on farms with

Table 1. FDA estimates of food-safety compliance costs (FDA 2013).

	Very small farms (less than $250,000 per year in sales)	Small farms ($250,000–$500,000 per year in sales)	Large farms (more than $500,000 per year in sales)
Characteristics of regulated farms			
Number of farms	26,947	4,693	8,571
Total acres	447,342	389,610	3,636,623
Average sales per farm	$75,279	$320,696	$2,638,384
Selected annual costs of food safety practices per farm (% of annual sales)			
Health and hygiene	$1,006 (1.34%)	$3,168 (0.99%)	$11,003 (0.42%)
Water provision with recordkeeping	$1,212 (1.61%)	$1,702 (0.53%)	$1,759 (0.07%)
Monitoring for animal intrusion	$373 (0.50%)	$1,247 (0.39%)	$2,481 (0.09%)
Sanitizing tools with recordkeeping	$581 (0.77%)	$2,228 (0.69%)	$5,001 (0.19%)
Personnel training	$725 (0.96%)	$2,701 (0.84%)	$6,763 (0.26%)
Personnel raining with recordkeeping	$172 (0.23%)	$172 (0.05%)	$439 (0.02%)
Total annual food safety costs per farm (% of annual sales)			
All costs (annualized over 7 years)	$4,697 (6.24%)	$12,972 (4.04%)	$30,566 (1.16%)
Costs in the first year	$8,260 (10.97%)	$20,470 (6.38%)	$38,133 (1.45%)

larger areas of surrounding seminatural vegetation. Instead, vegetation clearing was weakly correlated with an increase in pathogenic *E. coli* and *Salmonella* (Karp et al. 2015). One explanation for this trend is that vegetation can filter bacteria from runoff and sequester it in soils (Tate et al. 2006). Also, habitat removal could actually be favoring vectors such as deer mice that are more likely to transmit disease (Kilonzo et al. 2013).

Social impacts

Although heightened food-safety vigilance is intended to benefit public health by preventing foodborne illnesses, few studies have included the potential for unintended socioeconomic consequences, including increased production costs (especially for small to medium growers), farm consolidation, reduced socioeconomic diversity, and the reinforcement of ecologically damaging behavior and attitudes (Stuart 2008).

Installing and maintaining wildlife-deterrent fences and traps, testing water and soil samples, conducting self-audits, maintaining detailed records, obtaining third-party certification, hiring food safety staff, and forfeiting flooded crops cost growers time, money, and labor. For example, wildlife fences, which are often required by buyers but not by the LGMA, can cost tens to hundreds of thousands of dollars to install (Lowell et al. 2010).

These costs differ by farm size, but economic research on differential compliance costs remains sparse (Paggi et al. 2010). The only published survey on compliance costs in the Central Coast region found that, per acre, small and medium leafy greens growers (less than $1 million and $1 million–$10 million annual sales, respectively) pay nearly twice what large growers (more than $10 million annual sales) pay for food safety compliance (Hardesty and Kusunose 2009). At a federal level, the FDA estimated that of the approximately 40,000 farms that must comply with the FSMA's food safety standards, very small farms (less than $250,000 annual food sales), small farms ($250,000–$500,000), and large farms (more than $500,000) would respectively pay 6.2%, 4.0%, and 1.2% of their gross annual sales in food-safety costs (table 1; FDA 2013). These percentages are likely underestimates, because they do not include third-party audits, which reportedly cost $600–$1,000 or 0.6%–1.3% of a very small farm's annual sales.

Organic and conventional growers may also face different compliance costs. Although organic production accounts for 18% of produce acreage nationwide, organic farms occupy approximately 40% of the 171,000 acres that are currently treated with manures (FDA 2013). The FDA estimates that switching from manure to treated compost will cost organic farmers 1.6% to 2.5% of annual sales. The extent to which price premiums for organic produce could rise to mitigate expected compliance costs has not been evaluated.

Although empirical evidence on the effects of compliance costs in the Central Coast region is very limited, comparable food-safety reforms in other agrifood sectors indicate that small- and especially medium-sized farms that are unable to bear these costs may exit the industry (Knutson and Ribera 2011). Specifically, when the USDA's Food Safety Inspection Service implemented HACCP in the meat and poultry industry between 1997 and 2000, small- and medium-sized processing plants were more likely to exit the industry than larger plants, leading to widespread consolidation that persists today (Knutson and Ribera 2011). This trend is driven by larger firms' capacity to better absorb fixed costs and risks because of economies of scale (Woods et al. 2006). Although it is possible that small produce growers able to access direct-to-consumer market channels, such as farmer's markets, may avoid some food-safety compliance costs, the fields could also negatively affect water quality, pollination, pest control, soil quality, carbon storage, and biodiversity (Drinkwater et al. 1998, Kremen et al. 2002, Lowell et al. 2010, Kremen and Miles 2012, Chaplin-Kramer et al. 2013).

Intensive agriculture has impaired water quality in the Central Coast region (Los Huertos et al. 2001) and become a focus for regulation. Upstream in the Salinas watershed, communities import bottled drinking water because of groundwater nitrate contamination (Thomas 2013). Downstream, waterways in the Central Coast region drain into both the Elkhorn Slough National Estuarine Research Reserve and the larger Monterey Bay National Marine Sanctuary, regions that harbor 34 species of marine mammals and 525 species of fishes, including important commercial species whose populations have been affected by contamination (Hughes et al. 2015). Surrounded by farms, Elkhorn Slough is an impaired waterway with some of the highest nutrient concentrations of any estuary in the United States. (figure 2; Caffrey et al. 1997).

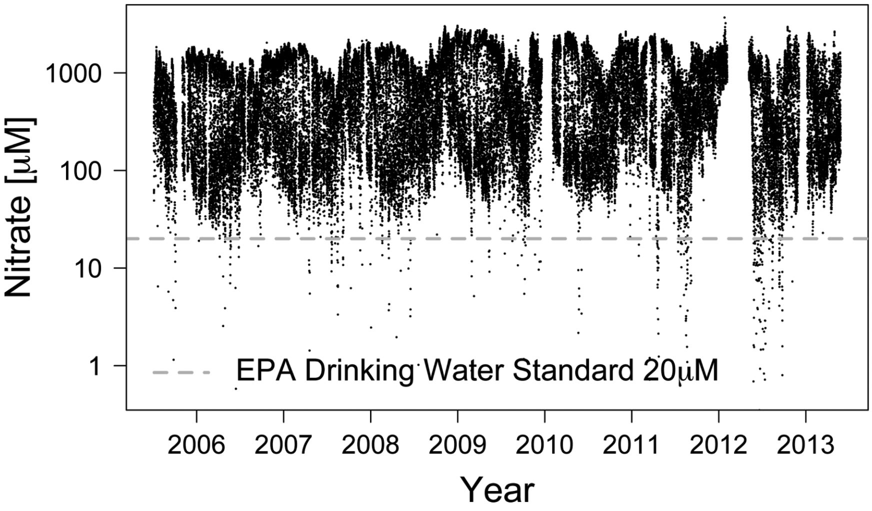


*Figure 2. The water quality (nitrate concentration) in the Elkhorn Slough at the old Salinas River channel. The Slough has some of the highest and most variable nitrate concentrations of any waterway in the United States. The EPA drinking water standard of 20 micromolar (μM) of nitrate (NO_3^-) is indicated along the bottom for comparative purposes. The data were acquired from the Monterey Bay Aquarium Research Institute's Land/Ocean Biogeochemical Observatory (*http://www.mbari.org/lobo*).*

documented experience of small producers in other agrifood sectors suggests that this strategy may not be sufficient when regulatory requirements are standardized (Wengle 2015).

Additional compliance costs to improve fresh produce safety are not generally matched by increased price premiums, because buyers use food-safety requirements to transfer risks and costs to growers, who have little control over farm-gate prices (Henson and Reardon 2005). Even if farmers comply with standards, an outbreak may still occur, potentially precipitating lost business, lawsuits, and even criminal charges. In 2013, federal investigators arrested two Colorado farmers in connection with a 2011 *Listeria monocytogenes* outbreak linked to contaminated cantaloupe. The arrest, according to the FDA, "sends the message that absolute care must be taken to ensure that deadly pathogens do not enter our food supply chain" (Elliot 2013). Although such a message may reassure a concerned public, state-imposed criminal charges add to existing anxiety—expressed to the authors in many conversations with growers—that liability for foodborne illness may bankrupt their farms. This anxiety may weigh more heavily on minority and immigrant farmers, who have historically faced disproportionate scrutiny from government regulators (Minkoff-Zern et al. 2011). Food-safety requirements can therefore become one of the many economic and social barriers that already make it difficult for these farmers to enter, or survive in, the fresh-produce agriculture sector.

Environmental impacts

Food-safety practices intended to minimize the potential for surrounding environments to contaminate produce

In response, water- and resource-conservation districts have worked with growers for decades to install vegetated treatment systems and retention ponds to prevent sediment erosion, sequester nutrients, and absorb toxic pesticides (Lowell et al. 2010, Zhang et al. 2010). However, these gains are threatened when growers discontinue such practices. Following the 2006 outbreak, one survey revealed that 15% of 181 growers (21% of leafy-greens growers) reported discontinuing conservation practices for food-safety concerns (Beretti and Stuart 2007). Resulting nutrient runoffs may increase eutrophication, marked by fundamental changes in biogeochemical cycling, harmful algal blooms, hypoxia, and declines in fisheries (Howarth et al. 2011). In the Elkhorn Slough watershed, habitat conversion and nutrient runoff have already caused the extirpation of 59% of fish species (Hughes et al. 2012). It is unknown, however, whether the amount of habitat removed for food-safety concerns is sufficient to further exacerbate these water-quality issues.

Vegetation removal may also cause declines in ecosystem services that bolster crop yields, such as pollination. Pollinators rely on natural habitat for food, nesting, and overwintering, and pollination often increases on fields located near natural habitat (Kremen et al. 2002). In the Central Coast region, strawberry farms surrounded by natural habitat hosted higher native bee abundances (figure 3). As European honeybees decline, habitat removal may threaten pollination and crop yields.

Similarly, insect predators prevent billions of dollars in crop damage each year in the United States. (Losey and

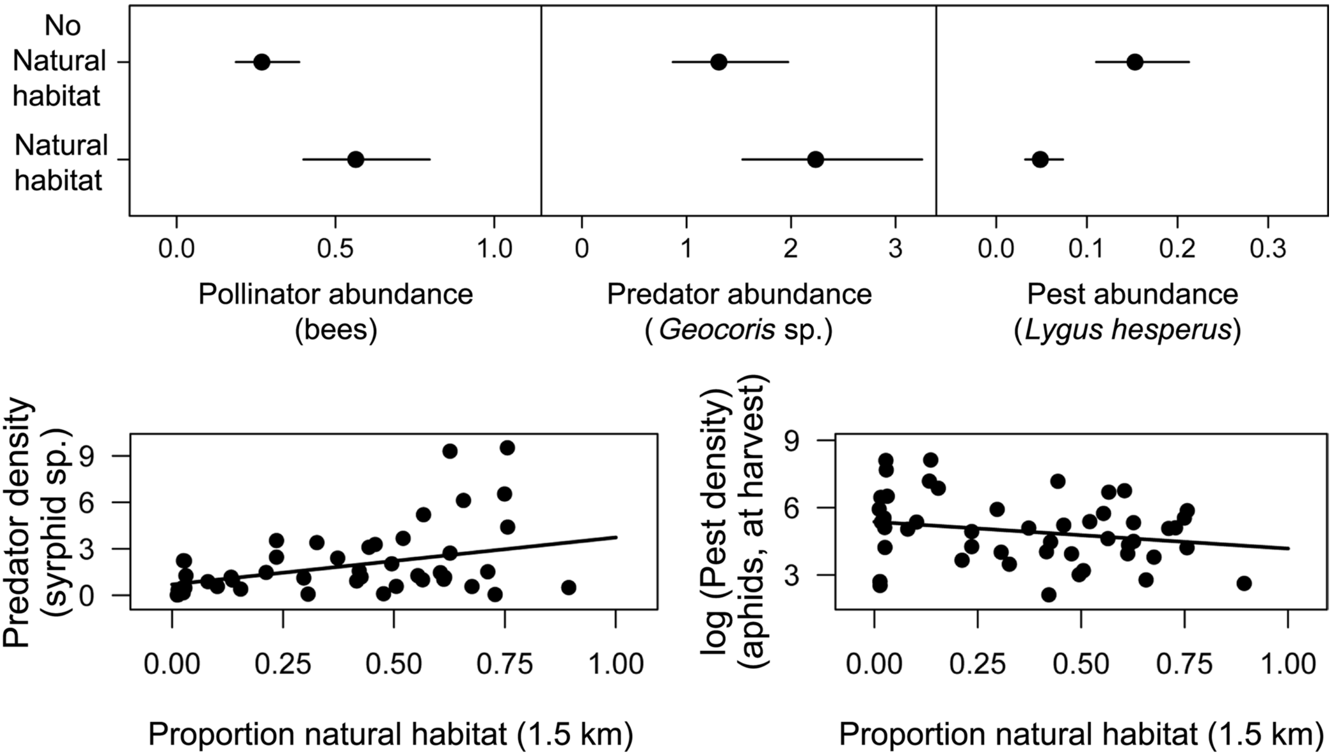


Figure 3. Pollinators, predators, and pests on 14 strawberry farms (top panels) and 24 broccoli farms (bottom panels) in the California Central Coast. Strawberry farms near natural habitat hosted more pollinators, marginally more predators, and fewer pests than farms surrounded by cropland. Predator abundance increased on broccoli farms surrounded by more natural habitat within 1.5 kilometers (km). In contrast, pest abundance measured just prior to harvest declined as the proportion of natural habitat increased (Chaplin-Kramer et al. 2013).

Vaughan 2006). Predator abundance and diversity are often higher on fields near natural habitat. In the Central Coast region, natural habitat was correlated with enhanced abundances of syrphid fly predators, reduced densities of aphid pests on broccoli (figure 3; Chaplin-Kramer et al. 2013), marginal increases of generalist predator abundances, and significant decreases of *Lygus* pests on strawberry (figure 3). Some pests, however, also rely on noncrop habitat to complete their lifecycles; therefore, habitat removal would not necessarily mitigate infestations of all pests. Still, if habitat removal is a net negative for natural pest control, then the practice could lead to a resurgence in conventional pesticides, with cascading health consequences for local farmworkers and neighboring communities. Prenatal pesticide exposure in the region has been shown to cause numerous negative health impacts on farmworker children, ranging from increased attention deficit/hyperactivity disorder to decreased IQ (Marks et al. 2010, Bouchard et al. 2011).

Beyond habitat removal, replacing compost applications rich in organic matter with other fertilizers may also impair ecosystem services. Composting increases soil organic matter, which can boost plant growth, biogeochemical cycling, soil micro- and macrofauna, water-holding capacity, plant-available water content, and resilience to drought (Kremen and Miles 2012). Replacing composts rich in organic matter with other fertilizers may supply nutrients alone, without supplying the crucial organic matter responsible for providing these ecosystem services. Furthermore, green and animal manures promote macronutrient and micronutrient retention in the soil (Gardner and Drinkwater 2009). Therefore, substituting other fertilizers for organic soil amendments may increase nutrient runoff, exacerbating water pollution.

Reducing applications of composts and removing natural vegetation may also diminish carbon storage. Belowground organic amendments promote soil-carbon retention and sequestration. One study calculated that if the application of animal or green manures was adopted throughout the United States' major maize and soybean growing regions, carbon sequestration increases could equal 1% to 2% of US fossil-fuel emissions (Drinkwater et al. 1998). Aboveground, trees, shrubs, and herbaceous vegetation that line field edges can hold substantial amounts of carbon.

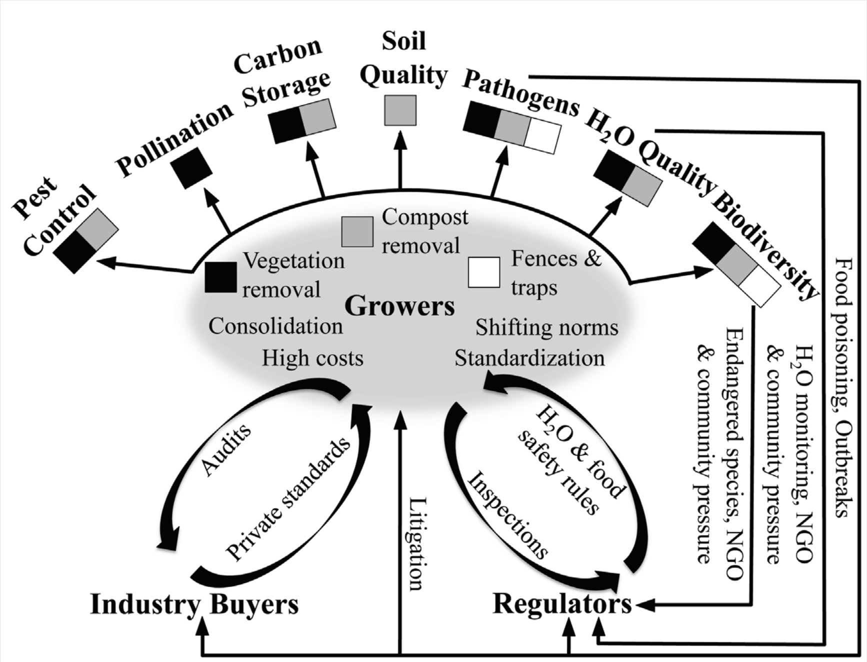
Finally, the California Central Coast hosts 80 animal and plant species listed or proposed for listing under the US Endangered Species Act, a major migratory bird flyway, and one of the largest marine sanctuaries in the United States. (Gennet et al. 2013). This substantial biodiversity has likely suffered from food-safety interventions, especially those practices designed to minimize wildlife intrusion. Bait traps filled with anticoagulant rodenticides, now ubiquitous

Box 1. The cascading consequences of a foodborne disease outbreak.

After a pathogen outbreak, lost sales from food recalls and liability concerns induce buyers to impose new farm-management requirements on growers. Government enforcement standardizes food-safety requirements and precipitates changes in production strategies. The compliance costs of new practices are unequally distributed among farmers, and higher burdens can drive small- to medium-sized and organic growers to exit agriculture. A potential result is a more homogenized agricultural system, in which farmland becomes consolidated among large growers that can afford food-safety practices.

Auditors visit the remaining growers and report food-safety compliance to regulators and buyers. Buyers may refuse entire harvests on the basis of auditor recommendations. Food-safety practices become entrenched after several years of privatized and often opaque interactions among buyers, auditors, and growers. Growers adopt farming norms that encourage sanitized growing environments.

Although not yet quantified in an explicit food-safety context, the effect on ecological systems is likely significant. Evidence from other systems suggests that removing vegetation, stopping compost applications, and lining field edges with fences and traps threaten biodiversity and alter significant ecological processes on and off farms, such as water quality, pest control, pollination, soil fertility, water-holding capacity, and carbon storage. Impairing ecosystem services may depress crop yields or encourage the greater use of inputs that require fossil-fuel expenditures or deplete groundwater supplies. Growers may also face conflicting regulations, such as if food-safety regulations recommend removing endangered-species habitat or wetlands that improve water quality.



throughout the Central Coast, not only kill target and nontarget wildlife but may also bioaccumulate in predators such as raptors and mountain lions (Lowell et al. 2010). Growers report targeting amphibians through poisoning streams, wells, and reservoirs with copper sulfate (Lowell et al. 2010). Several threatened and endangered amphibians and fish use these water sources, prompting conflict between food-safety regulations and endangered-species management. The widespread removal of native vegetation adjacent to farms further threatens these and other species. For example, removing riparian vegetation increases water temperatures, making streams less hospitable for endangered steelhead (Thompson LC et al. 2008, Lowell et al. 2010). More generally, habitat removal constrains wildlife corridors, disrupting wildlife movements (Penrod et al. 2000). The extensive network of wildlife fences erected along the Salinas river riparian corridor exacerbates this disruption.

Conclusions

As foodborne diseases associated with consumption of fresh produce appear to continue to increase in frequency (Lynch et al. 2009, Painter et al. 2013), what has happened on the Central Coast could provide insight into how future disease outbreaks may similarly catalyze rapid and reverberating changes within agricultural systems (box 1). In the near term, changes in the Central Coast region reflect possible trajectories for fresh produce farming throughout the United States as the FDA begins to regulate produce safety nationwide. The rules authorized under the FSMA will affect approximately 4.5 million acres of US farmland, as well as approximately

15,000 foreign farms through import controls (FDA 2013). Structurally, the FSMA and the LGMA are very similar. There are, however, several notable exceptions. For example, the FSMA's most recently proposed produce rule does not require a waiting period in between compost application and harvest (LGMA 2013, FDA 2014). It also states explicitly that it does not require habitat removal. Nonetheless, the FSMA rules, like those of the LGMA, represent a minimum standard, and produce buyers may still impose more stringent demands, leading to further unintended ecological and social effects nationwide.

Effective strategies to prevent foodborne outbreaks are needed, but there are many approaches to minimize risk; not all are equal in impact on people and nature. There is a pressing need to weigh options with respect to their unintended consequences beyond the rightful concern of food safety. The ongoing implementation and development of federal food-safety policy provide important opportunities to researchers, farmers, nongovernmental organizations, and agencies for fostering the spread of practices that consciously co-manage agricultural, environmental, and health objectives. To develop more appropriate agency rules and guidance, implementation practices, legislative amendments, and industry best practices, targeted, interdisciplinary research should assess both the direct and indirect social and environmental impacts of food-safety interventions.

We first suggest evaluating produce-safety practices to determine their efficacy in mitigating contamination risk. Observational experiments could evaluate whether and to what extent pathogens decline after new farming practices are implemented. For example, replacing natural habitat with bare-ground buffers may not stop the species most likely to be disease vectors (Lowell et al. 2010, Karp et al. 2015). Second, future research should seek to inform strategies for mitigating primary pathogen sources. A landscape-scale analysis could inform risk-reduction strategies by documenting how pathogens disseminate from disease reservoirs (e.g., livestock production facilities) to production fields. For example, Stawn and colleagues (2013) surveyed *Listeria*, Shiga-toxin producing *E. Coli* (STEC), and *Salmonella* across five farms in New York State and found that *Listeria* prevalence increased near pastures. Similarly, several studies have shown that both pathogenic and generic *E. coli* prevalences are higher near grazed lands (Benjamin et al. 2013, Karp et al. 2015).

Third, research is needed to characterize the precise relationships among food-safety standards (both regulatory and market based), farming practices, the market structure, ecosystem services, and foodborne-illness outcomes. In addition, the extent to which the implementation of science-based food-safety regulations may mitigate legal liability concerns, a key driver of private-sector requirements, must be determined. There is good conceptual—but not concrete—evidence that produce-safety practices disrupt the ecosystem services that are crucial for sustainability and on which growers and downstream stakeholders rely. Likewise, current indications suggest that food-safety regulations favor large businesses over small and push growers toward farm models that may align poorly with emerging markets for local and sustainable produce. There is already evidence that organic growers began using practices such as monocropping following the creation of federal standards prescribing what "organic" means (Guthman 2004). A key question is whether produce safety represents another pressure on growers to continue consolidating and to adopt industrial practices instead of integrating ecological interactions into farming. Ultimately, interdisciplinary research that evaluates pathogen-management practices in relation to the pressures and constraints felt by growers and industry is needed to elucidate co-management strategies for conservation and food safety.

For the last century, many agricultural policies have prioritized maximizing short-term yields. However, there is increasing recognition that agroecosystems should be managed to yield diverse, multifunctional benefits, including sustaining ecosystem services that ensure agricultural production over the long term (Kremen and Miles 2012). However, as the case of food safety in California's Central Coast attests, targeting farm-level management alone is insufficient. The interactions among policy, on-farm practice, surrounding landscapes, and ecosystem services must be considered in concert. Co-managing agricultural systems for food production, rural livelihoods, conservation, and health is possible, but it requires nuanced evaluations of the feedback and tradeoffs inherent in complex socioecological systems.

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