# Environmental Impacts of Sustainable Agriculture in Practice and at Scale Evidence From Mexico

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# The Need for Sustainable Intensification

- Food system redesign and climate adaptation necessary to ensuring global food security
- Sustainable Agricultural Intensification emphasized as a key strategy for achieving food security and environmental goals
- Little causal evidence on effectiveness of sustainable agriculture technologies in practice and at scale

# The Gap We're Filling

*[…] there is little research on putting the components together in viable production systems, and in quantifying [sustainable intensification's] potential in terms of both production and environmental performance in farmers' fields rather than small manicured research plots.*

PERSPECTIVE
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nature sustainability
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## A global perspective on sustainable intensification research

Kenneth G. Cassman and Patricio Grassini

**Despite general agreement that meeting food demand without further loss of natural ecosystems requires sustainable intensification, there is little dialogue about the research agenda needed to achieve it. To that end, we evaluate current trajectories towards sustainable intensification, review published research on the topic, identify missing links, and propose a prioritization framework to fill gaps. Although progress towards sustainable intensification is behind schedule, we are optimistic that current trends can get back on course assuming a well-prioritized and adequately funded research portfolio and appropriate policies and institutions to support it.**

In the broadest sense, sustainable intensification (SI) seeks to increase crop and livestock yields and associated economic returns per unit time and land without negative impacts on soil and water resources or the integrity of associated non-agricultural ecosystems[1]. Success in implementing an SI approach is best quantified by metrics that measure system outputs (again, broad sense) in terms of: (1) yield; (2) input requirements to achieve that yield; (3) impact on soil quality defined as the capacity to support crop yields and input-use efficiencies[2]; and (4) impact on natural resources and ecosystems affected by the production system. Hence, in addition to yield, SI must be evaluated by efficiency metrics such as yield per unit input of energy, water and nutrients rather than by the source or type of inputs (for example, organic or conventional, genetically modified organism (GMO) or non-GMO), and by impacts on a broad array of ecosystem services with particular concern for water quality and biodiversity[3].

The potential to achieve SI and the degree to which it is achieved can be considered from a local field or farm scale, to regional, national and global scales. At a local level, SI of small-scale subsistence farms might include judicious use of fertilizer and greater diversification with high-value vegetable crops, or addition of fishponds and livestock that utilize by-products from crop production and allow return of animal manures to help maintain soil fertility. On large-scale mechanized farms, intensification typically involves manipulating crop and soil management practices to eke out further efficiencies in capture of resources and conversion to yield. Examples include use of shorter-maturing crop varieties to allow production of an additional crop each year on the same field, improved nutrient management practices that better synchronize nutrient supply with crop demand during the growing season without excess or deficiency, conservation tillage that increases infiltration of rainfall and reduced runoff, and cover crops to recover fertilizer nutrients not taken up by the cash crop and to protect soil from erosion, to name a few. In all cases, the capacity of soil to provide water and nutrients to support crop growth must be maintained or enhanced to ensure sustainability in terms of soil quality.

The call for 'sustainable intensification' originally focused on the need to move beyond the seed, fertilizer and pesticide technologies that support modern, high-yield conventional agriculture, towards more 'restorative' production systems that rely less on external inputs and more on leveraging internal resources and ecological processes to supply nutrients and control pests[4]. Since then, justification for SI, and closely related 'ecological intensification,' has expanded to address national and global concerns about agriculture's negative impact on environmental quality and natural resources on one hand, and need to achieve substantial increases in crop yields on existing farmland to avoid further loss of natural habitat on the other[1,5]. Of particular concern is conversion of rainforests, grassland savannahs and wetlands to crop production and the associated loss of biodiversity and soil carbon stocks, the latter contributing considerably to anthropogenic greenhouse gas (GHG) emissions. And while SI is necessary to address these challenges, it is not sufficient because success in conserving natural habitat also requires good governance, appropriate legal frameworks for land tenure, and international agreements to ensure that progress towards SI on existing farmland achieves desired environmental outcomes[5].

Evaluating the potential of existing agricultural systems to undergo SI at national and global scales provides insight about land, water and energy requirements to ensure adequate food supply while also addressing concerns about climate change and biodiversity. A global lens helps illuminate broad trends and drivers of future food supply and commodity prices in international markets, which in turn provides critical input to national research and development (R&D) priorities because most countries currently rely on imports to meet food demand. Effective priority setting at a national scale identifies the crops, cropping systems, regions and technologies most likely to advance SI given endowments of climate, soil and water resources.

### Global food security on a razor's edge

After years of relatively stable and declining prices for the world's major staple food crops, the new millennium has brought considerably more turmoil in commodity markets. Since year 2000 there have been three episodes of abrupt spikes in prices of major staple grains compared to much greater price stability during the preceding two decades (Fig. 1). In each case relatively small deficits in global food supply attributed to drought, heatwave, flooding, or a combination of these stresses in one or more countries caused international commodity prices to increase by 50% or more. Accompanying these price spikes were episodes of political unrest in countries dependent on imports[6,7]. Although export restrictions imposed by a few

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*Cassman & Grassini (2020) Nat. Sus.*

# The Gap We're Filling

*We recently reviewed the effects of specified changes to farming systems on agricultural productivity, and found that in the past six years, few studies considered more than one or two different sustainability metrics. Less surprising but equally problematic was the shortage of long-term and broad-scale studies.*

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comment

## How scalable is sustainable intensification?

Sustainable intensification is a concept of growing importance, yet it is in danger of becoming scientifically obsolete because of the diversity of meanings it has acquired. To avoid this, it is important to consider the various scales on which it can aid progress towards feeding human populations while also protecting the environment.

Richard M. Gunton, Leslie G. Firbank, Alex Inman and D. Michael Winter

Put simply, sustainable intensification (SI) describes approaches to global agriculture that would increase yields without adverse environmental impact and without putting more land under cultivation. The term's origin dates back to the 1990s, when it was developed in an exclusively African context[1]. It became prominent as a scientifically meaningful objective for global agricultural policies and development only in the late 2000s (Fig. 1). The concept was promoted by an influential report by the Royal Society[2], which contributed to the UK government embracing the term and establishing an SI research platform (SIP) in 2014. However, 'sustainable' remains a contested term. We recently reviewed the effects of specified changes to farming systems on agricultural productivity[3], and found that in the past six years, few studies considered more than one or two different sustainability metrics. Less surprising but equally problematic was the shortage of long-term and broad-scale studies.

There are now signs that the SI bandwagon is faltering. Some activists have long considered SI an oxymoron[4], but scientists have also begun to question its adequacy as a helpful concept for addressing food security[5]. It has been suggested that the way SI has been defined and developed "lacks engagement with established principles that are central to sustainability"[6]. Indeed, SI has acquired such a range of meanings in its 20-year history that use of the term itself may be unsustainable. Although there is agreement that SI should not prescribe particular techniques, its objective as presented in contemporary academic and policy documents can be anything from increased on-farm efficiency to the education of subsistence-farming communities. At the root of this divergence are diverse views of how farming and conservation should relate to each other.

**The need for a sustainable definition**

Definitions can shape our thinking and ambiguity can hide a paradigm shift. The history of the term biodiversity illustrates how the application of different paradigms to the same word causes confusion. Widely adopted in the 1980s, 'biodiversity' was defined as including the diversity of all living things at the genetic, species and assemblage levels. In practice, genetic diversity was too hard to quantify and ecosystem diversity too vague, so attention focused on species diversity, usually species richness. This implied that all species were of equal value and encouraged the conservation of species-rich, climax or plagioclimax assemblages as being the least replaceable in a short timescale. Understandably, however, ecologists wanted more than a bean-counting role and so began to use the word biodiversity to refer to the variety of ecological roles in a community (functional diversity). This approach accepts that different species may occupy the same general niche, and that the roles of rare species might be very small, or even redundant. Now, increasingly, 'biodiversity' is used to mean assemblages of diverse living organisms *per se* rather than any measure of diversity, and the ecosystem services literature values those assemblages that benefit people, whether directly or indirectly[7]. The focus shifts towards common taxa with recognized functions (for example, insect pollinators) rather than rare and obscure ones, and the monetary valuation of ecosystem services allows biodiversity offsetting, whereby habitat loss can be justified by habitat restoration elsewhere, losses in species richness notwithstanding[8]. 'Sustainable intensification' now risks also going through such a sequence of semantic shifts by which one meaning of a term becomes the enemy of another.

The words sustainable and intensification are also widely interpreted. 'Sustainable' can evoke such diverse concepts as financial profitability, management of environmental impact, maintenance of natural capital and building resilience against rapid change, as well as more elusive concepts such as naturalness. 'Intensification' often carries connotations of large-scale and industrial farming, of monoculture crops and caged or low-welfare livestock. But the combination of these two terms has an even wider semantic scope. Early definitions of SI emphasized the notion of agronomic efficiency — maximizing the output to input ratio so as not to waste resources. This focus can be criticized for paying insufficient attention to the temporal dimension of sustainability. Some advocates go further to argue that SI should account not just for how much food can be produced, both now and into the future, but also the types, variety and nutritional content of the food. This leads to definitions of SI as "the process of delivering more safe, nutritious food per unit of input resource, whilst allowing the current generation to meet its needs without compromising the ability of future generations to meet their own needs"[9]. Then, giving more cultural weight to the 'sustainability' element in a global context, some argue for inclusion of social and ethical considerations such as labour rights, animal welfare and social equality — hence claims that sustainable intensification "needs to be mindful of the social, economic and ethical context within which food production activities take place"[10]. This breadth of meaning calls into question the usefulness of SI as a concept: for example, interviews with 30 agricultural





*Gunton et al. (2016) Nat. Plants*

# How This Study Fits In

- MasAgro: Large-scale extension program in Mexico promoting Conservation Agriculture beginning in 2012
- Causal evidence of environmental improvements and subsequent health consequences
- Suggestive evidence of profitability relative to alternative technologies
- Demonstration of one mechanism through which Conservation Agriculture generates environmental benefits: reduced agricultural burning

# Roadmap

Conservation Agriculture and MasAgro

Data

Air Pollution+Infant Mortality Results

Profit Results

Mechanism: Agricultural Burning

Conclusion

# Conservation Agriculture

**Minimal soil disturbance, constant soil cover**, and crop rotation

- One of the major Sustainable Intensification strategies promoted worldwide (Pretty et al., 2018)
- Aimed primarily at improving soil health

# Potential Environmental Benefits

Aside from improving soil quality, Conservation Agriculture may improve air quality when practiced at scale

- Reduced-tillage found to be correlated with less dust generated during planting period in US (Behrer & Lobell, 2022)
- Crop residue used as soil cover replaces agricultural burning, shown to have a number of negative consequences (Rangel & Vogl, 2019; He et al., 2020; Graff Zivin et al., 2020; Lai et al., 2022; Pullabhotla et al., 2023)

# MasAgro

Nation-wide extension effort in Mexico launched in 2012 with technical backing from CIMMYT[1]

How it works:

- Techniques developed at Experimental Stations
- Side-by-side plots managed by farmers (Modules)
- Farmers work with technician to adopt new technologies on Extension Plots
- Diffusion to Impact Areas observed by extension technicians

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# Data: Analysis Sample

492 localities with minimal agricultural employment

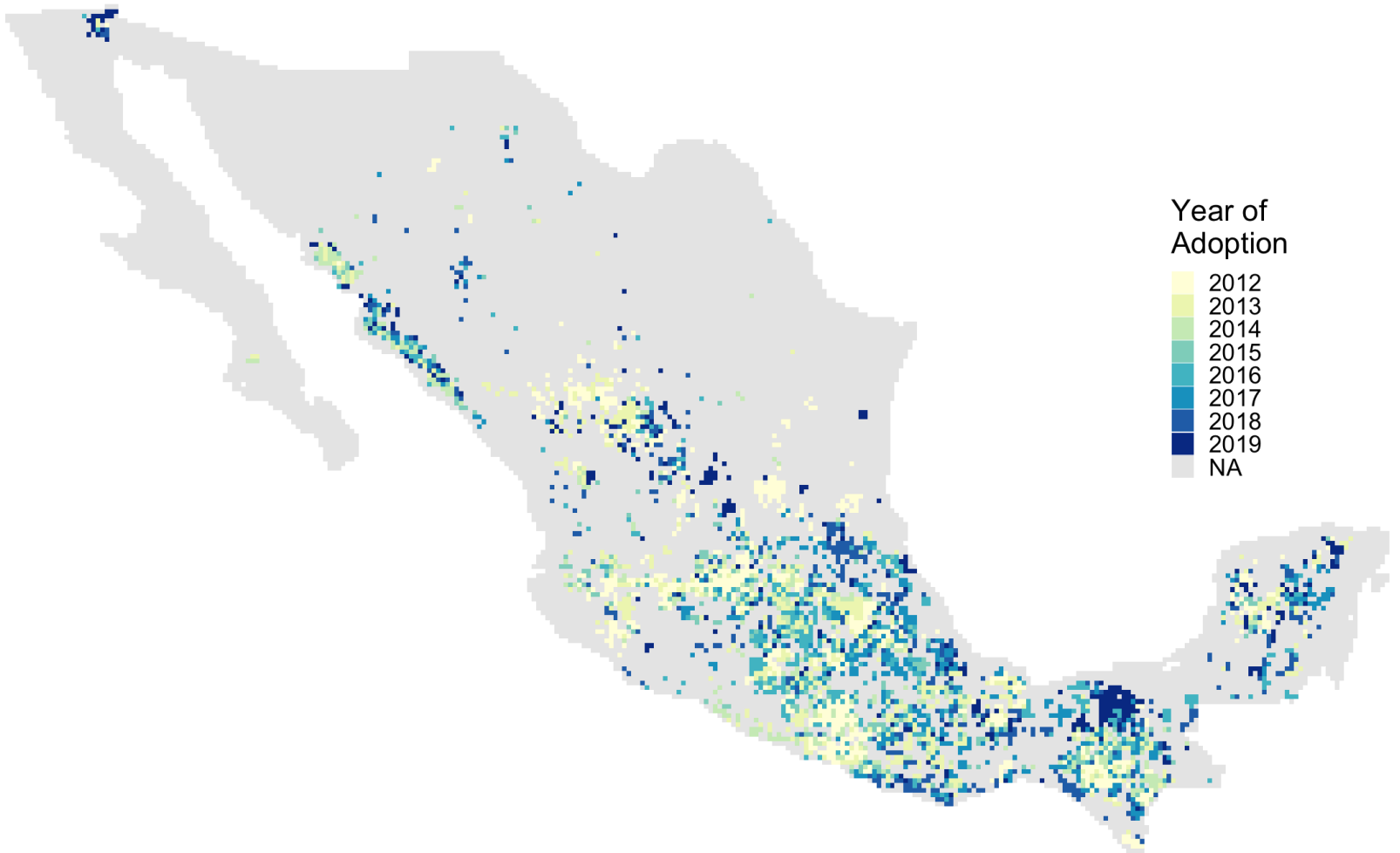
# Data: Technology and Production

Extension technicians record data in the Bitácora Electrónica MasAgro (BEM)

- **Modules**: Input usage and costs, output produced, sales prices
- **All plots**: Location, promoted technologies employed, year of adoption

Conservation Agriculture is the most widely adopted technology (32%)

# Diffusion of Conservation Agriculture



# Data: Wind Direction

ERA5 re-analysis

- Combines weather station data with satellite imagery to make a global gridded weather dataset
- Daily wind direction and speed
- 0.25 degree resolution

# Data: Air Quality

Two sets of air quality measurements

- **SINAICA Monitors:** High quality sensors located in 78 localities (PM 10)
- **Aerosol Optical Depth (AOD):** Daily satellite-imagery based measurements, correlated with PM 10/2.5 (Zou (2021), Gendron-Carrier et al. (2022))

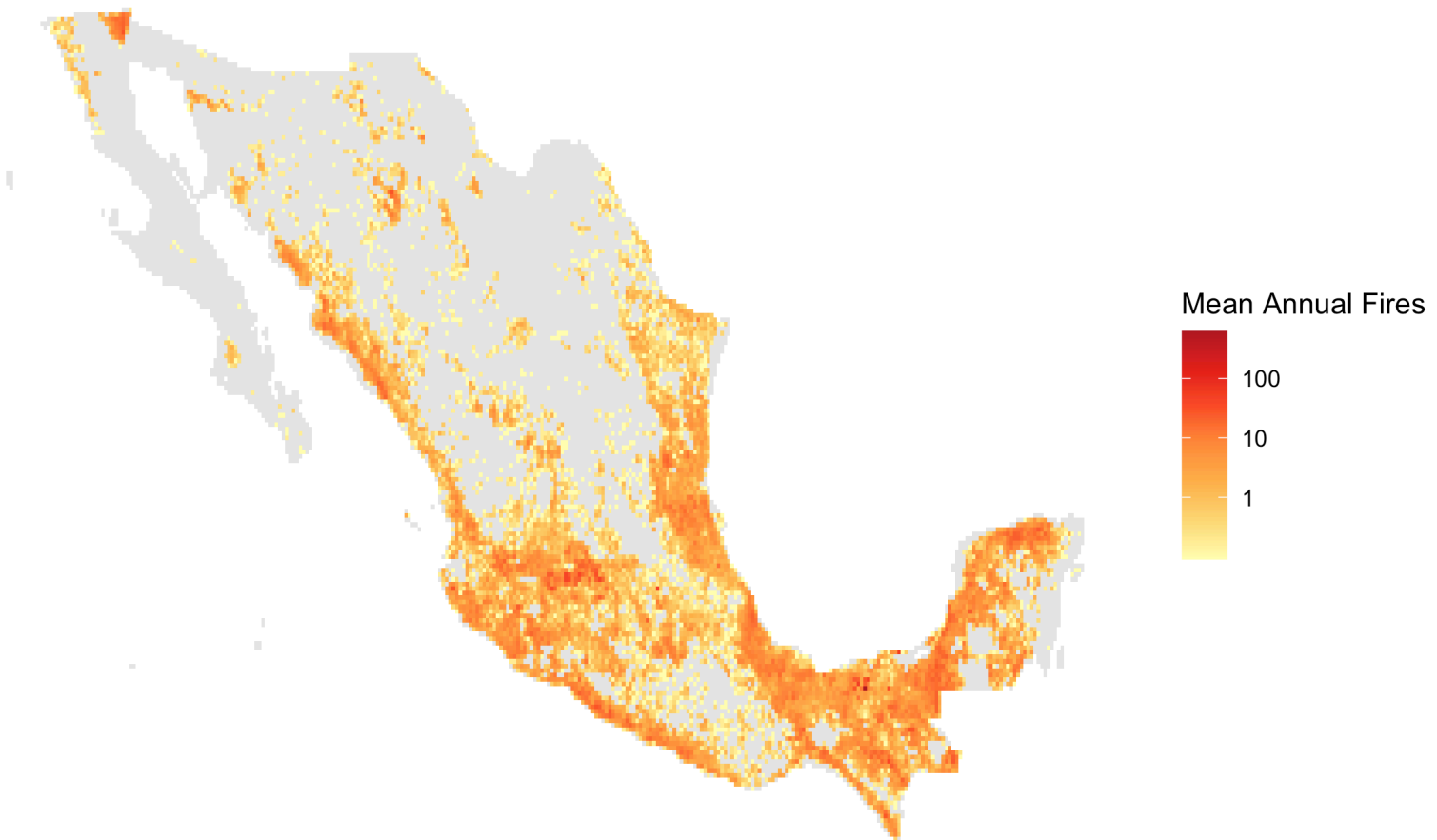
# Data: Infant Mortality

Publicly available administrative data on births and deaths in Mexico

- **Deaths:** Month and year of birth/death, locality of residence
- **Births:** Month and year of birth, locality only available starting in 2013
- Cannot link birth and death data

# Data: MODIS Themal Anomalies and Fire

Daily measurements of fire in 1km × 1km pixels. Restricted to agricultural land



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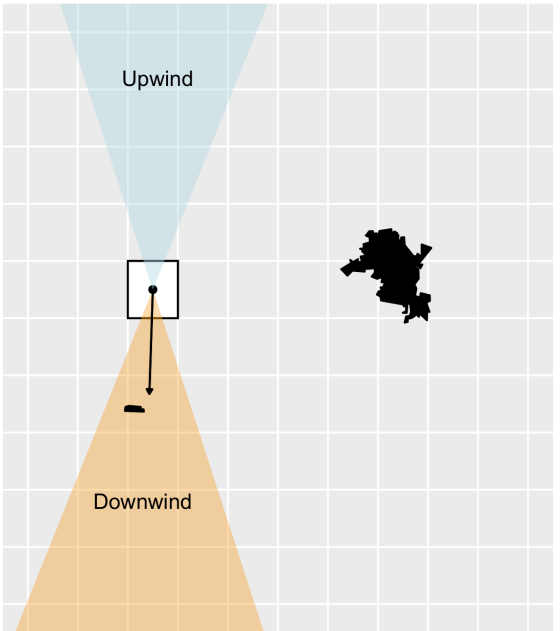
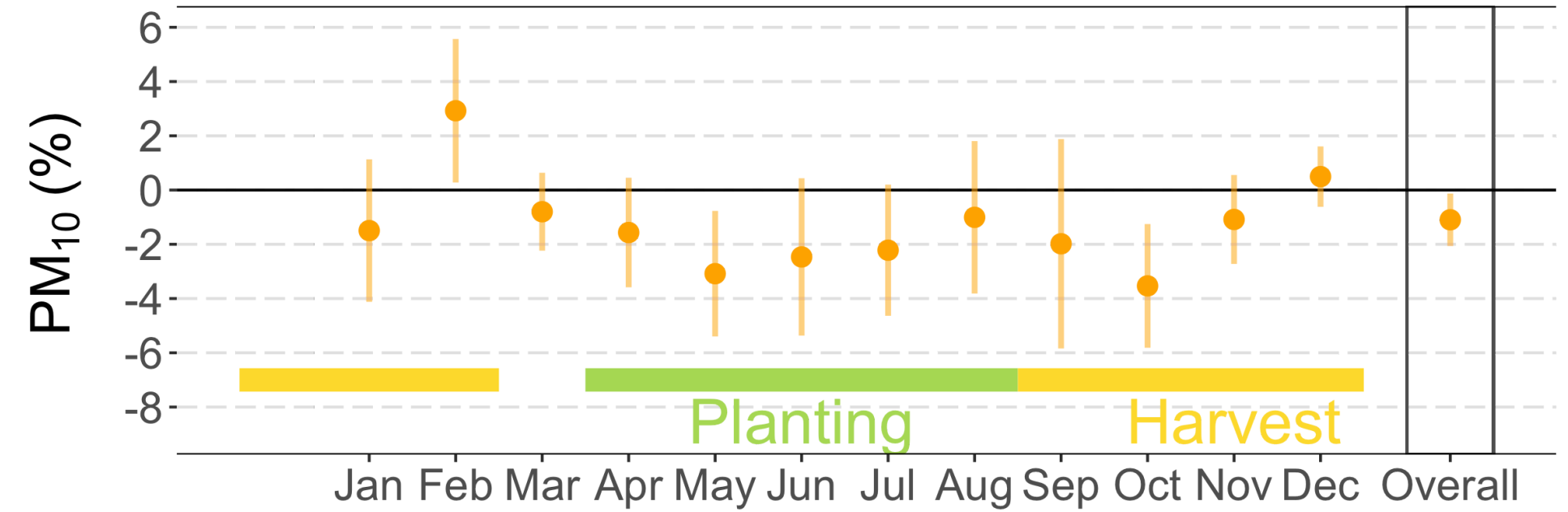
# Research Design

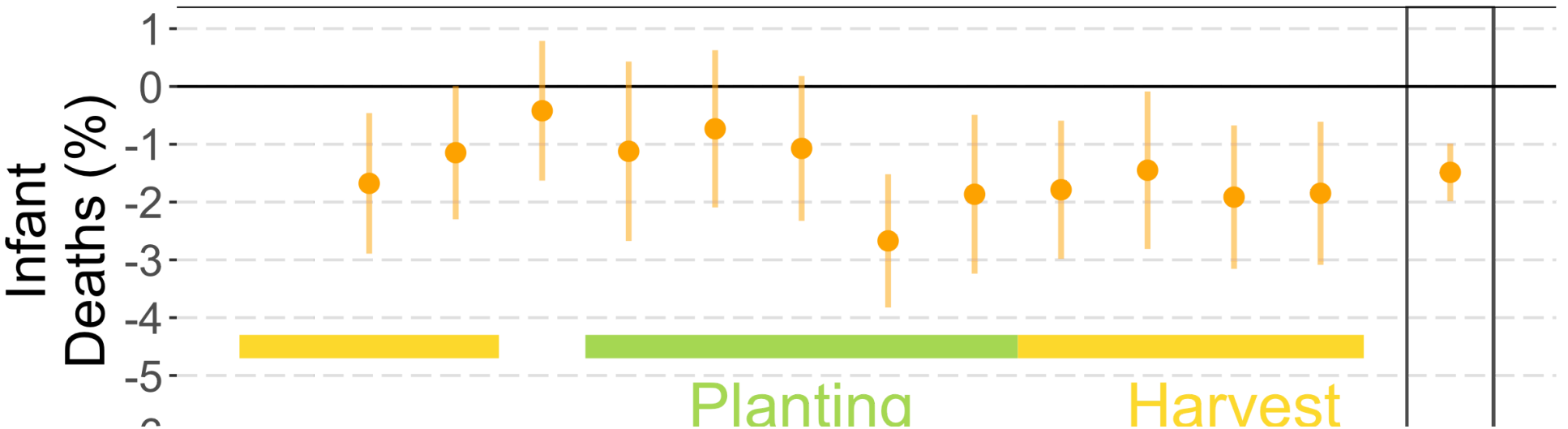
Compare effect of locality being downwind from cells before and after adoption of Conservation Agriculture




$$
\begin{aligned}
Y_{l,m,t} &= \alpha_{l,m} + \delta_t \\
&+ \beta_m^{down} Downwind\ Post_{l,m,t} + \gamma_m^{down} Downwind\ Ever_{l,m,t} \\
&+ \beta_m^{up} Upwind\ Post_{l,m,t} + \gamma_m^{up} Upwind\ Ever_{l,m,t} \\
&+ \beta_m^{lat} Lateral\ Post_{l,m,t} + \gamma_m^{lat} Lateral\ Ever_{l,m,t} \\
&+ \varepsilon_{l,m,t}
\end{aligned}
$$

# Monthly Downwind Effects



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# Profits

Effects of Conservation Agriculture on Profits

| Outcome | Profit/ha<br>(1) | Log(Profit/ha)<br>(2) |
|---|---|---|
| Extension | 1737.7<br>(58.8)<br>[<0.01] | 0.407<br>(0.012)<br>[<0.01] |
| Extension × CA Module | 584.8<br>(111.3)<br>[<0.01] | 0.020<br>(0.022)<br>[0.36] |
| Observations | 24098 | 17700 |

*Notes:* Profits are top and bottom Winsorized at 2.5%. All regressions include field fixed effects. Standard errors clustered at the producer-level are in parentheses. P-values are in brackets.

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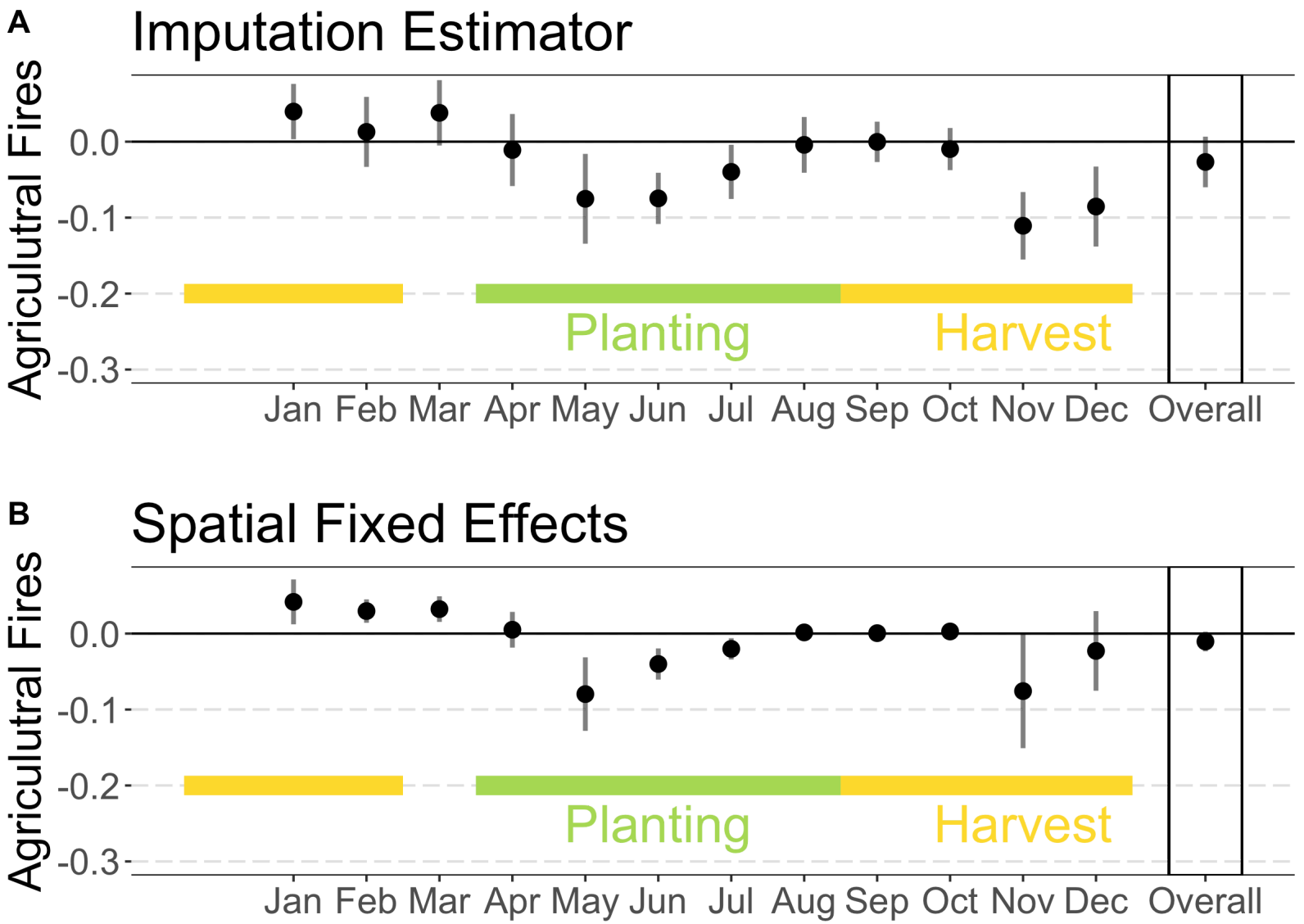
# Agricultural Fires



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# Conclusion

- 10-20% reduction in agricultural 🔥
- 1.3% reduction in $PM_{10}$ concentration in downwind localities
- Back-of-Envelope: 11.4K deaths averted 2012-2019, VSL benefits ~31x greater than cost of extension
- Suggestive evidence that Conservation Agriculture is weakly more profitable than alternative technologies

**Thanks!**

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# Appendix: Imputation Estimator

Model of untreated potential outcomes:

$$Ag\ Fires_{i,t}(0) = \alpha_i + \delta_t + \eta_t Ag\ Area_i + \varepsilon_{i,t}$$

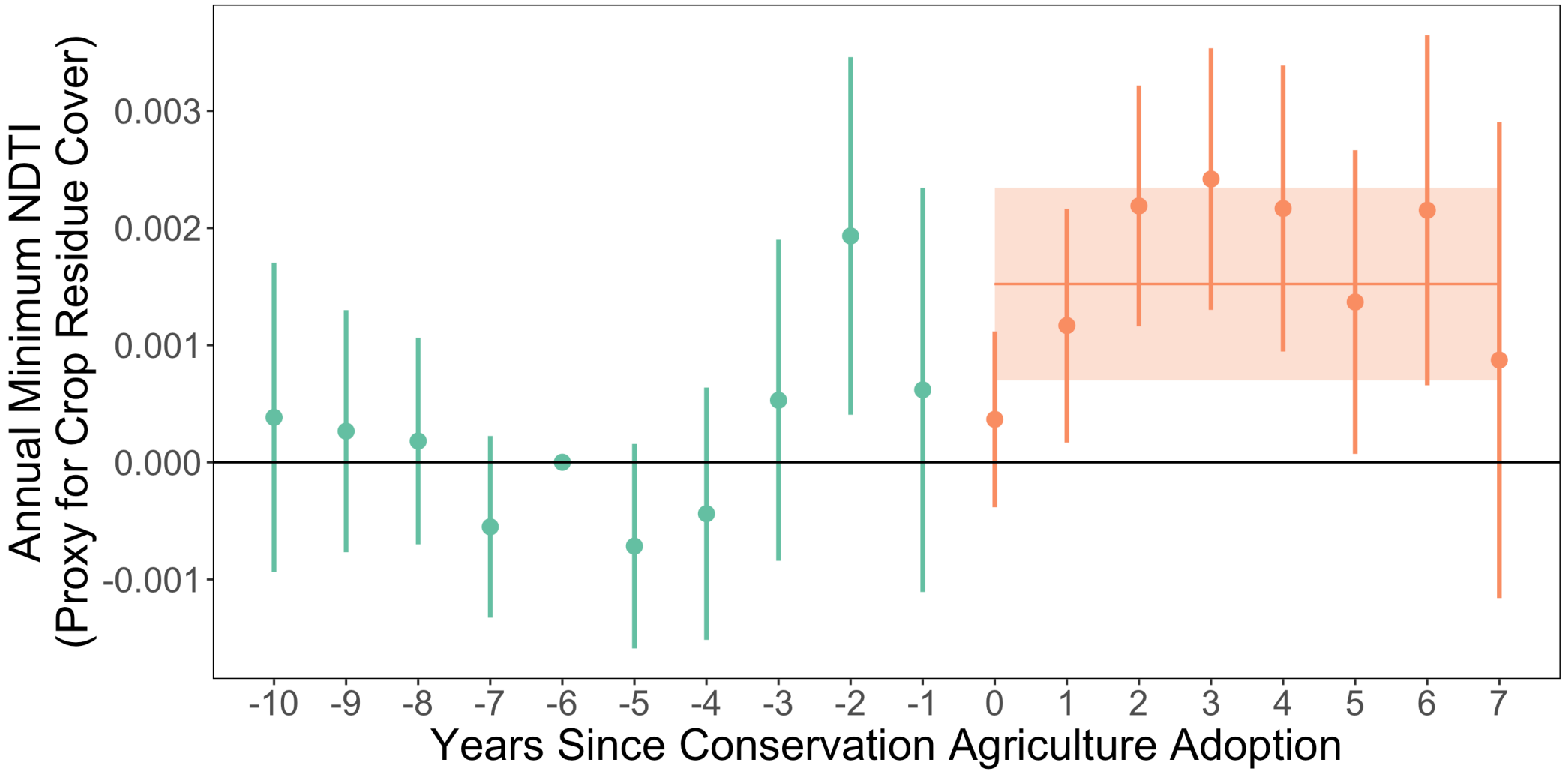
Subtract imputed untreated outcomes from treated obs

$$\widehat{\tau}_{i,t} = Ag\ Fires_{i,t}(1) - \widehat{Ag\ Fires}_{i,t}(0)$$

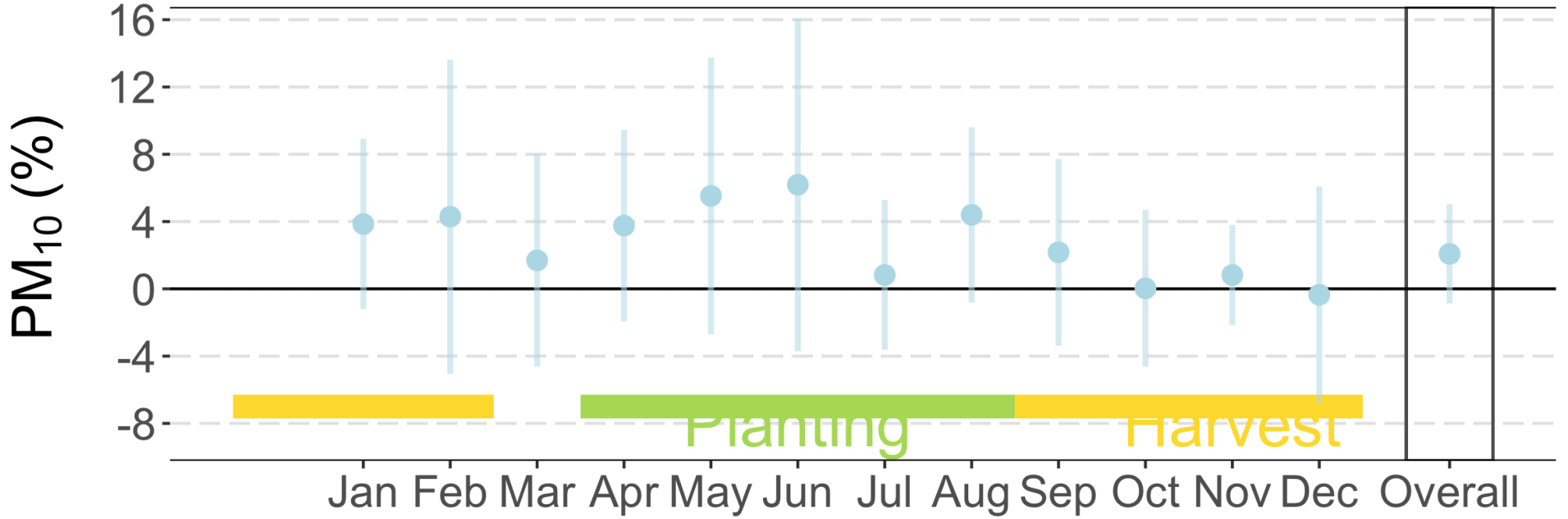
Average among observations of interest, e.g. a particular event time $\Omega_k = \{i, t : t - E_{i,t} = k\}$

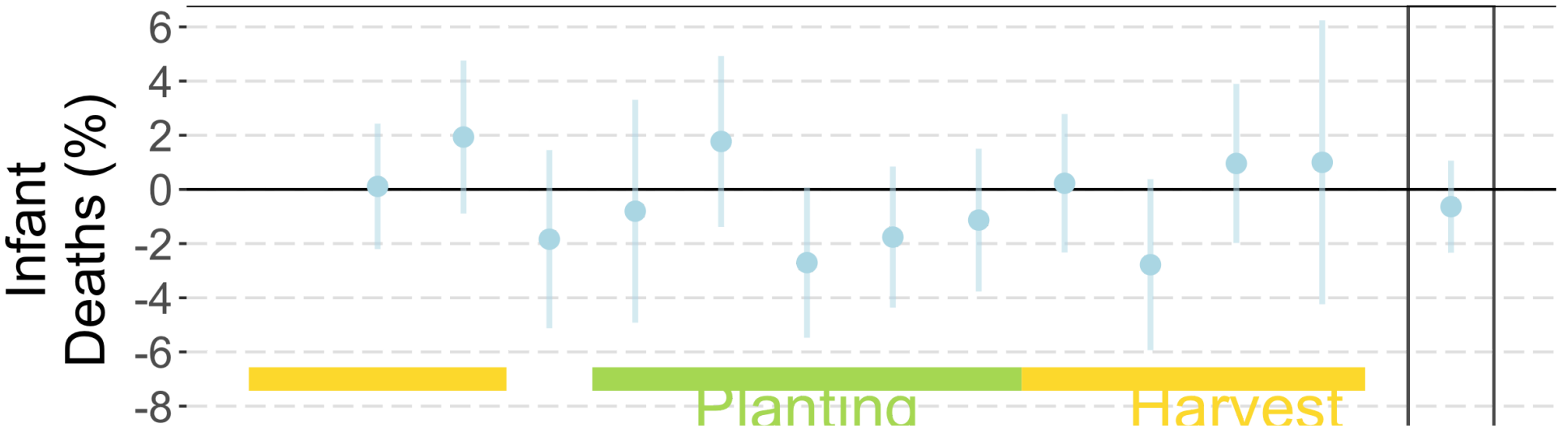
$$\hat{\tau}_k = \frac{1}{|\Omega_k|} \sum_{\{i,t \in \Omega_k\}} \widehat{\tau}_{i,t}$$

# Appendix: Adoption Persistence

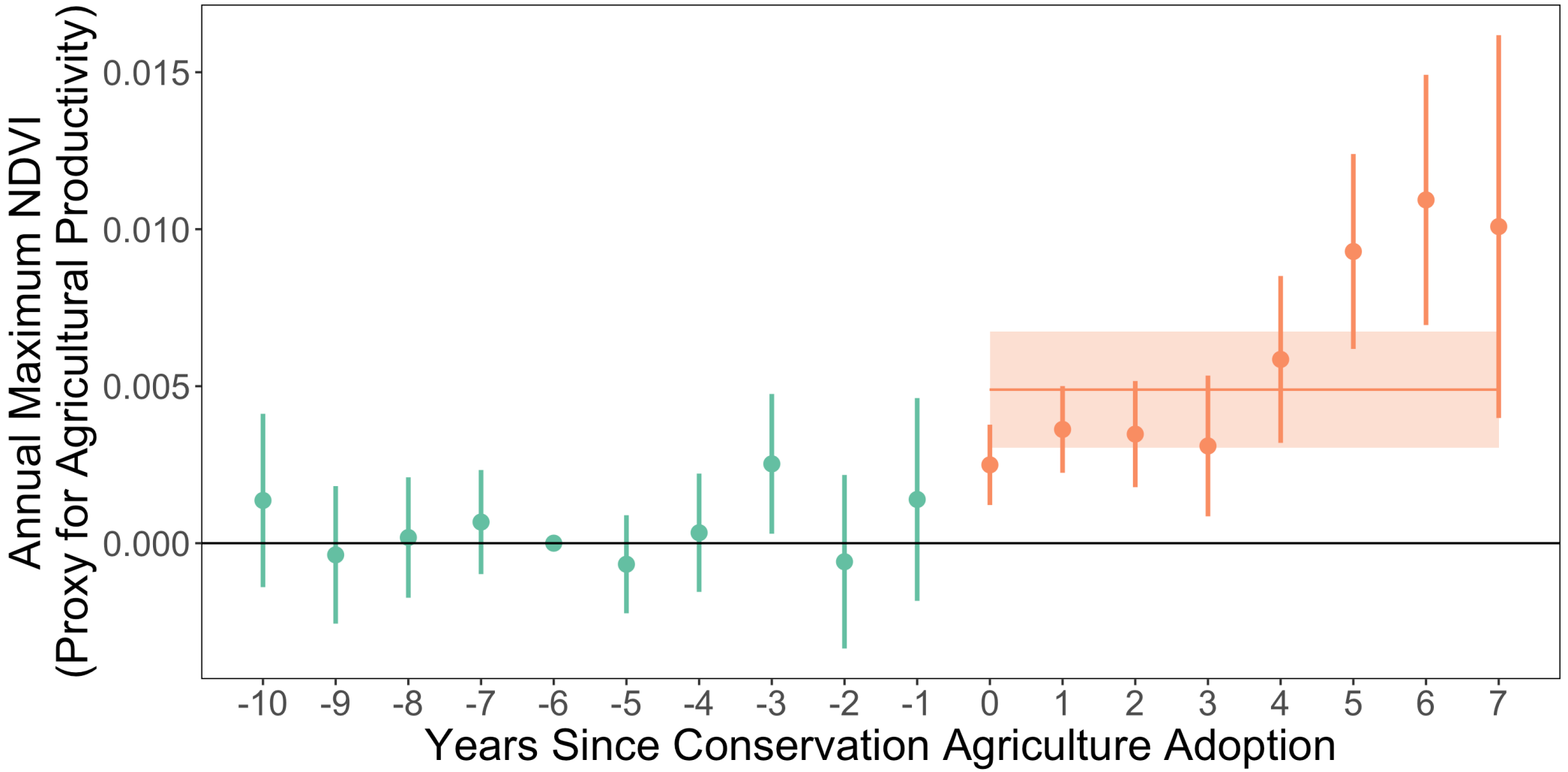


# Appendix: Placebo Test



# Appendix: Agricultural Productivity



# Agricultural Fires