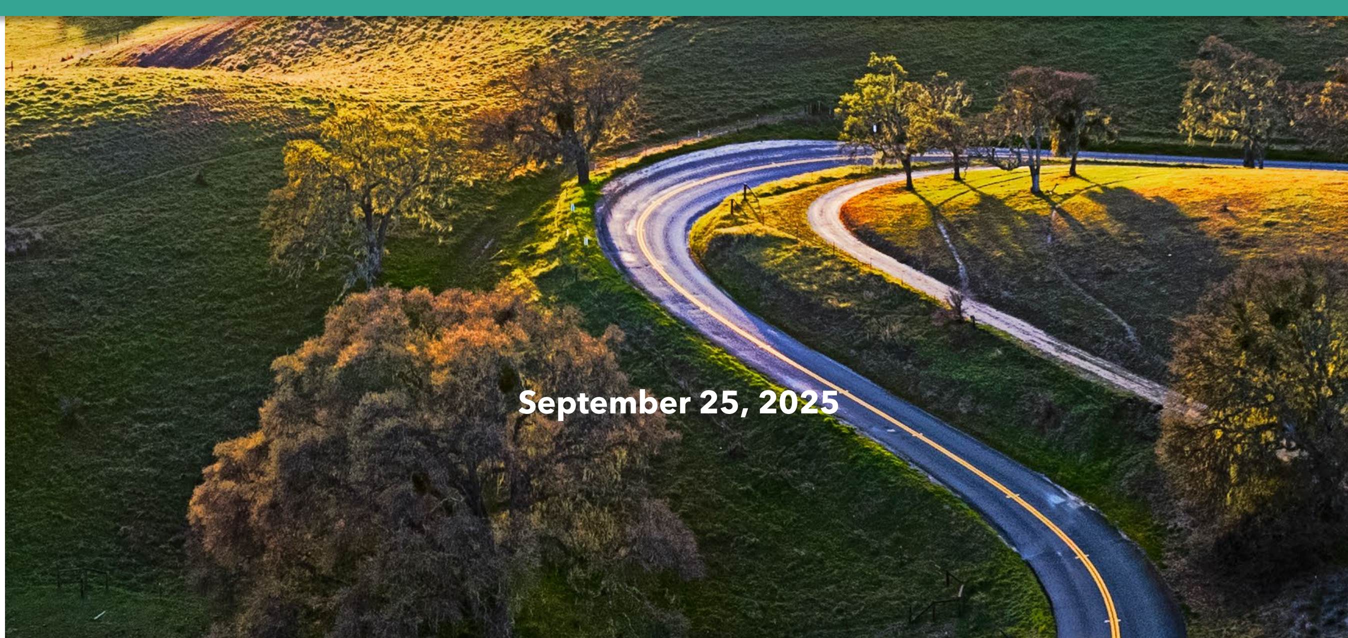
CALIFORNIA
AIR RESOURCES BOARD

September 2025

Five-Year Strategic Research Plan for Fiscal Years 2025 to 2030



September 25, 2025

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This report is available for viewing or download on the CARB's Research Program website at *ww2.arb.ca.gov/our-work/programs/research-planning*.

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List of Acronyms

3NOP	3-nitrooxypropanol
AB	Assembly Bill
AC	Air conditioning
ACF	*Advanced Clean Fleets*
ACS	Alternative charging solutions
ACT	*Advanced Clean Trucks*
AIM	American Innovation and Manufacturing (AIM) Act
AR6	Sixth Assessment Report
ASCENT	*Atmospheric Science and Chemistry mEasurement NeTwork*
ATCM	*Airborne Toxic Control Measure*
BC	Black carbon
BVOC	Biogenic volatile organic compounds
BWTW	Brake- and tire-wear
BWWW	Train brake-wear and wheel/rail-wear
CADD	*California Dairy and Livestock Database*
CADEM	California Dairy Emission Model
CALFIRE	*California Department of Forestry and Fire Protection*
CalNex	*California Research at the Nexus of Air Quality and Climate Change campaign*
CalSMP	*California Satellite Methane Project*
CAMP	*Community Air Monitoring Plan*
CAPP	*Community Air Protection Program*
CARB	*California Air Resources Board*
CBO	Community-Based Organization
CCHVI	Climate Change and Health Vulnerability Indicators
CDFA	*California Department of Food and Agriculture*
CDPR	*California Department of Pesticide Regulation*
CEC	*California Energy Commission*
CEIDARS	*California Emissions Inventory Data Analysis and Reporting System*
CEPAM	*California Emission Projection Analysis Model*
CERP	Community Emissions Reduction Plans
CH_4	*Methane*
CMAQ	*Community Multiscale Air Quality Modeling System*
CO	*Carbon monoxide*
CRC	Coordinating Research Council
DAC	Disadvantaged Community

DEF	Diesel exhaust fluid
DISCOVER-AQ	*Deriving Information on Surface Conditions from COlumn and VERtically Resolved Observations Relevant to Air Quality*
DNDC	*DeNitrification-DeComposition*
DPF	Diesel particulate filter
DPM	Diesel particulate matter
DRRP	*Diesel Risk Reduction Plan*
ED	Emergency Department
EJ	*Environmental Justice*
EJAC	*Environmental Justice Advisory Committee*
EJSM	Environmental justice screening method
EMA	Engine Manufacturers Association
EMFAC	*On-road emissions factor model*
EtO	Ethylene oxide
FIREX-AQ	*Fire Influence on Regional to Global Environments – Air Quality campaign*
FOFEM	*First-Order Fire Effects Model*
g/bhp-hr	grams per brake horsepower-hour
GHG	Greenhouse gas
GWP	*Global warming potential*
HAP	*Hazardous Air Pollutants*
HC	Hydrocarbons
HD	Heavy-duty
HDDV	Heavy-duty diesel vehicle
HDV	Heavy-duty vehicle
HF	Hydraulic fracturing
HFC	Hydrofluorocarbons
HFO	Hydrofluoroolefins
IAQ	Indoor air quality
ICT	*Innovative Clean Transit*
IPCC	*International Panel for Climate Change*
JPL	*Jet Propulsion Laboratory*
LCFS	*Low Carbon Fuel Standard*
LCS	Low-cost sensors
LDV	Light-duty vehicle
MATES	*Multiple Air Toxics Exposure Study*
MECA	Manufacturers of Emission Controls Association
MY	Model year

N_2O	*Nitrous oxide*
NAAQS	*National Ambient Air Quality Standards*
NGO	Non-governmental organizations
NH_3	Ammonia
NO	Nitric oxide
NOx	Oxides of nitrogen
NWL	Natural and Working Lands
O_3	Ozone
OBD	On-board diagnostics
OEHHA	*Office of Environmental Health Hazard Assessment*
OVOC	Oxygenated volatile organic compounds
ORE	Off-road equipment
PACE	*Potential Phased Advanced Clean Equipment*
PAIR	*Portside Air Quality Improvement and Relief Program*
PAMS	Portable Activity Measurement Systems
PCBTF	Para-chlorobenzotrifluoride
PEAQS	Portable Emissions AcQuisition System
PEMS	Portable Emission Measurement Systems
PFAS	*Perfluoroalkyl and polyfluoroalkyl substances*
PHEV	Plug-in hybrid electric vehicles
PM	*Particulate matter*
PM2.5	*Airborne particulate matter with an aerodynamic diameter equal to or smaller than 2.5 micrometers*
PM10	Airborne particulate matter with an aerodynamic diameter equal to or smaller than 10 micrometers
PN	Particle number
ppm	Parts per million
ppt	Parts-per-trillion
PTR-MS	Proton-Transfer-Reaction Mass Spectrometer
RECAP-CA	Re-Evaluating the Chemistry of Air Pollution in California
RFP	Request for proposal
RSC	*Research Screening Committee*
RSD	Remote sensing device
RWQCB	*Regional Water Quality Control Boards*
SB	Senate Bill
SCAQMD	*South Coast Air Quality Management District*
SCR	Selective catalytic reduction
SIP	*State Implementation Plan*
SJV	San Joaquin Valley

SLCP	*Short-lived Climate Pollutants*
SMERP	Subject Matter Expert Review Panel
SO_2	Sulfur dioxide
SOA	Secondary organic aerosol
SOC	Soil organic carbon
SoCAB	South Coast Air Basin
SPHERE	San Joaquin valley Pollution and Health Environment REsearch study
TAC	Toxic Air Contaminants
TARTA	Portable real-time metals analysis instrument
TFA	Trifluoroacetic acid
TMR	Total mixed rations
TOG	Total Organic Gases
U.S. EPA	*United States Environmental Protection Agency*
UC/CSU	University of California/California State University
UFP	Ultra-fine particles
VMT	Vehicle miles traveled
VOC	Volatile organic compounds
WUI	Wildland-urban-interface
WW	Wheel-wear
ZE ORE	Zero-emission off-road equipment
ZEV	Zero-emission vehicle

Executive Summary

The California Air Resources Board (CARB) is dedicated to protecting public health, welfare, and ecological resources by effectively reducing air pollutants while carefully considering economic impacts. CARB's Research Program plays an important role in shaping California's air quality and climate policies by identifying emerging vulnerabilities; informing emission inventories, models, and measurement methods that can support cost-effective interventions; advancing innovative strategies to reduce air pollution and greenhouse gas (GHG) emissions; and evaluating the health and environmental benefits of mitigation efforts. It also supports decision-makers in navigating complex trade-offs across environmental, economic, and public health priorities. While focused on California, CARB's research provides valuable insights for other regions confronting similar challenges.

CARB's Five-Year Strategic Research Plan (Five-Year Plan) is organized into five chapters: *Health*, *Ambient Air Quality*, *Climate*, *Mobile Sources*, and *Sustainable Transportation, Housing, and Communities*, with environmental justice and economic analysis integrated throughout. Many of the California-specific research needs may be relevant to other jurisdictions, particularly where federal research may no longer be available. Each chapter also emphasizes the importance of assessing both the benefits of action and the costs of inaction on public health, the environment, and the economy. For details on past and current research, key policy drivers, and future priorities, refer to the individual chapters of the Five-Year Plan.

Importance of Robust Research and Science in Public Policy

Robust, evidence-based research provides the foundation for transparent, accountable, and forward-looking decisions. It also supports policies that can adapt to changing environmental and economic conditions while pursuing long-term goals, such as mitigating climate change and achieving healthy air for all Californians. Without reliable data and rigorous analysis, policymaking can become reactive, vulnerable to misinformation, and less effective at addressing complex challenges that harm public health, the environment, and the economy. CARB is committed to building on past achievements through continuing robust, data-driven research developed through a transparent process to support policymaking.

This approach is increasingly important as a growing body of scientific evidence highlights the significant human and economic costs of inaction on air pollution and climate change:

- **Air pollution:** Eliminating emissions of primary fine particulate matter (PM2.5), sulfur dioxide (SO_2), and oxides of nitrogen (NOx) from the electric power, transportation, building, and industrial sectors in the U.S. could prevent an estimated 46,900 to 59,400 premature deaths each year. The associated health-related economic benefits are estimated to range from $537 billion to $678 billion.[1]

- **Wildfire Smoke:** In California, over 52,000 premature deaths were linked to PM2.5 from wildland fires between 2008 and 2018, with an estimated economic impact exceeding $430 billion.[2]
- **Extreme Heat:** From 2013 to 2022, seven major heat events in California resulted in 460 deaths and approximately $5 billion in health-related costs.[3]
- **Compound Climate Events:** The risk of mortality increases by 21% on days with both extreme heat and high air pollution compared to nonextreme days.[4]
- **Sea-Level Rise and Infrastructure Risk:** Sea-level rise and intensified storms could put an estimated $8 to $10 billion in California property at risk by 2050.[5]
- **Agricultural Impacts:** Estimated crop revenue losses were $1.3 billion for 2021 and $1.7 billion for 2022 compared to 2019 conditions, with the largest proportion of the losses in the Central Valley due to drought-idled land.[6]
- **Energy and Labor:** Rising temperatures are projected to increase electricity demand and reduce labor productivity, particularly for outdoor workers in agriculture and construction.[7, 8]
- **Healthcare Costs:** Climate-related conditions, such as cardiovascular diseases, increasingly burden healthcare systems and public budgets.[9]

[1] *Mailloux, Nicholas A., et al. "Nationwide and regional PM2. 5-related air quality health benefits from the removal of energy-related emissions in the United States." GeoHealth 6.5 (2022): e2022GH000603.*

[2] *Connolly, Rachel, et al. "Mortality attributable to PM2.5 from wildland fires in California from 2008 to 2018." Science advances 10.23 (2024): eadl1252.*

[3] *California Department of Insurance (2024). Impact of extreme heat to California's people, infrastructure, and economy*.

[4] *Rahman, Md Mostafijur, et al. "The effects of coexposure to extremes of heat and particulate air pollution on mortality in California: implications for climate change." American Journal of Respiratory and Critical Care Medicine 206.9 (2022): 1117-1127.*

[5] *California Legislative Analyst's Office (2020). What Threat Does Sea-Level Rise Pose to California?*

[6] *University of California, Merced (2022). Economic Impacts of the 2020-22 Drought on California Agriculture*

[7] *Climate Change and the Health of Workers | US EPA*.

[8] *Chapter 9: Populations of Concern | Climate and Health Assessment*.

[9] *Jacobsen, Alan P., et al. "Climate change and the prevention of cardiovascular disease." American Journal of Preventive Cardiology 12 (2022): 100391.*

- **Equity and Vulnerability:** Environmental stressors, such as wildfire smoke, extreme heat, and deteriorating air quality, often disproportionately affect low-income communities, children, older adults, and outdoor workers.[10, 11]

While these figures do not represent the full extent of impacts related to air pollution and climate, they highlight the critical role of scientific research in understanding and preparing for future risks. Quantifying the human and economic costs of inaction—alongside the benefits of proactive intervention—can help public policies remain evidence-based and aligned with long-term health, environmental, and resilience goals. CARB's strategic Research Program remains committed to advancing research that supports California's air quality and climate objectives, while also providing insights that can inform efforts in other jurisdictions. To promote transparency and inclusivity, CARB's Research Program is expanding outreach efforts to engage broader audiences and increase the use and application of research findings.

As federal funding challenges for critical research emerge, CARB is also committed to identifying defunded and underfunded research that could support near-term action and should be prioritized for other funding sources, such as philanthropy. This information will be posted to CARB's website and updated regularly. While states and non-governmental funding cannot fill all the gaps that may emerge from federal action, CARB believes in the criticality of research efforts that support action on a national level to protect public health and reduce GHGs.

Environmental Justice, Equity, and Accessibility

CARB remains committed to integrating *environmental justice* and *racial equity* perspectives into its research to strengthen the agency's programs and help policies deliver benefits to all Californians. Environmental justice means the fair treatment and meaningful involvement of people of all races, cultures, incomes, and national origins in the development, adoption, implementation, and enforcement of environmental laws, regulations, and policies.[12] CARB's Racial Equity Framework defines racial equity as both an outcome and a process. As an outcome, it envisions a future where race no longer predicts life outcomes and where outcomes improve for all groups. As a process, it ensures that people and communities historically underrepresented or underserved are meaningfully involved in shaping and implementing CARB's policies, programs, and practices that affect their lives.

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[10] *Balmes, John R. "Where there's wildfire, there's smoke." New England Journal of Medicine 378.10 (2018): 881-883.*

[11] *Morello-Frosch, Rachel, et al. "Environmental justice and regional inequality in southern California: implications for future research." Environmental health perspectives 110.suppl 2 (2002): 149-154.*

[12] *California Code, GOV 65040.12*.

CARB engages with communities throughout California to create research ideas, carry out research projects, and share research outcomes. These efforts in research include, but are not limited to, *Community Research Roadmaps*, which bring together academic researchers, local residents, community-based organizations, and Tribes to co-develop community-identified research priorities related to CARB's goals. A current example of this is the *Imperial Valley Community-Focused Collaborative Research Plan*. Community Research Roadmaps are an important aspect of CARB's research planning process and a key method for integrating strategies that address opportunity gaps and disparities in CARB's Research Program. *Appendix C - Environmental Justice and Racial Equity in CARB Research* also provides a comprehensive overview of CARB's efforts to advance community-centered research and adopt tools that support fair and inclusive outcomes. Individual initiatives are also described in the research chapters.

To improve accessibility, CARB provides research summaries and translated materials, particularly for health-protective recommendations, and has expanded public engagement through surveys, polls, and virtual meetings to foster broader participation. Development of the Five-Year Strategic Research Plan (Five-Year Plan) involved collaboration with community-based organizations (CBOs) and included a series of in-person meetings focused on community priorities aligned with CARB's mission. CARB remains committed to expanding outreach and increasing the accessibility and use of its research findings.

Looking ahead, continued coordination with federal, state, and local agencies, as well as local communities, will be essential for shaping research priorities and informing effective air quality and climate policy.

Synopsis of Future Research Priorities

Chapter 1. Health

CARB's *Health Research* plays an important role in advancing the understanding of the health benefits associated with air quality and climate change mitigation policies. This includes both quantitative and qualitative co-benefits, as well as the health impacts and missed opportunities that result from inaction. A key priority is examining how socioeconomic factors influence air pollution exposure, climate vulnerability, and health disparities. Research on cumulative impacts remains essential, particularly in communities affected by multiple air pollution sources and non-chemical stressors. CARB is expected to continue evaluating the health co-benefits of carbon reduction measures and developing effective outreach and health communication efforts to ensure communities have the information and tools useful for reducing associated health risks. These efforts can support informed decision-making in California and other jurisdictions.

Chapter 2. Ambient Air Quality

CARB's *Ambient Air Quality Research* supports California's efforts to attain the health-based California and National Ambient Air Quality Standards (CAAQS & NAAQS) set under state and federal law, respectively. California develops State Implementation Plans (SIP) to meet those mandated standards. Research in this area aims to improve understanding of directly emitted pollutants, such as PM2.5, ammonia, volatile organic compounds (VOCs), and air toxics, as well as the atmospheric conditions that lead to the formation of additional harmful pollutants like ozone and oxygenated organic aerosols. Advanced measurement techniques, laboratory experiments, and intensive field campaigns are leveraged to support long-term monitoring and inform air quality forecasting models. Key priorities include investigating the sources of VOCs, especially air toxics from industrial, agricultural, and transportation sectors, and assessing their impacts on air quality, public health, and the environment. Future studies will also examine how changing meteorological patterns and land management practices influence air quality, especially as climate change drives more extreme heat, wildfire smoke, and related stressors. The findings are expected to inform the SIP strategies and help address air quality disparities. As many other states face similar challenges in meeting current and previous air quality standards, CARB will prioritize sharing findings to support broader national efforts.

Chapter 3. Climate

CARB's *Climate Research* priorities support the Scoping Plan and inform strategies to achieve California's statutory GHG emission reduction goals, while assessing the consequences of inaction. These efforts generate scientific insights that can guide climate actions in other states. Key focus areas include quantifying carbon sequestration potential in natural and working lands (NWL), such as coastal wetlands, forests, and agricultural soils, and evaluating sustainable land management practices and emission reduction technologies in agriculture. Other priorities include research on short-lived climate pollutants, such as methane from dairies, low-global warming potential refrigerants, and the impacts of wildfires on carbon storage and land management. CARB also emphasizes assessing the health, environmental, and economic impacts of inaction on climate change, especially across different communities, and evaluating the co-benefits of integrated air quality and climate strategies across diverse populations.

Chapter 4. Mobile Sources

CARB's *Mobile Sources Research* priorities focus on improving emissions characterization across all vehicle types, with an emphasis on high-emitting vehicles and malfunctioning vehicles. This includes deploying advanced sensors and data analysis to monitor emissions from legacy vehicles and assess the effectiveness of both current and future regulations. As zero-emission vehicles (ZEVs) become more prevalent, research is expected to focus on improving ZEV efficiency, optimizing operational characteristics to support broader adoption, and leveraging vehicle batteries to support grid stability. The scientific findings can offer valuable insights to California and other states pursuing cleaner transportation.[13] Research also targets emission reductions from off-road vehicles and accelerating ZEV adoption in that sector. A growing focus is on non-exhaust emissions, such as brake, tire, and wheel wear, to better understand their air quality and public health impacts. Remote sensing technologies will continue to play a key role in tracking emissions and supporting CARB's *Community Air Protection Program*.

Chapter 5. Sustainable Transportation, Housing, and Communities

CARB's *Sustainable Transportation, Housing, and Communities Research* will continue to support the development of sustainable, inclusive, and accessible communities. Key research areas include strategies to increase access to affordable housing, reduce transportation-related emissions, and advance the decarbonization of buildings and transportation systems. A primary focus is evaluating the effectiveness of policies aimed at reducing vehicle-miles-traveled (VMT), promoting high-occupancy transportation, and fostering more walkable, bikeable, and transit-accessible communities. Future research priorities include understanding how the use of low-carbon materials affects housing costs and development. CARB is also expected to work on identifying tools, metrics, and policy coordination strategies to help accelerate sustainable and resilient community growth. As jurisdictions across the country pursue similar goals,[14, 15] CARB's research can offer valuable insights to inform efforts beyond California.

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[13] *Affordable Clean Cars Coalition | Initiatives | U.S. Climate Alliance*.

[14] *Congestion Pricing Program in New York - MTA*.

[15] *Six Months In, Governor Hochul Highlights Success of Congestion Pricing: Traffic Is Down, Business Is Up, and Critical Investments Are Being Made to Improve Transit | Governor Kathy Hochul*.

CARB's Research Program

Introduction to the Five-Year Strategic Research Plan

The Legislature established CARB's Research Program in 1971 to provide the scientific foundation for effective air pollution control. The Research Program follows a structured annual research planning process to identify and fund research aligned with CARB's *mission* and emerging needs. With an annual budget of $4 million to $8 million, approximately 5 to 12 projects are selected each year. This process incorporates community engagement, internal expertise, and collaboration with academic institutions, government agencies, and non-governmental organizations (NGOs) to prioritize research that delivers actionable data, addresses air quality and climate challenges, and evaluates the consequences of inaction. While centered on California, the research it supports may offer insights applicable to other jurisdictions.

As California's lead agency for air quality and climate change mitigation, CARB collaborates with local air districts and federal partners to achieve health-based air quality standards through effective control strategies. From clean vehicle and fuel requirements to innovative climate solutions, California's policies have served as national and global models. These efforts are grounded in rigorous, science-based research that supports and strengthens regulations and initiatives.

To align its annual research planning with California's long-term policy goals, CARB developed the Five-Year Strategic Research Plan (Five-Year Plan) for 2025 to 2030. The Five-Year Plan outlines past and current research, key policy drivers, and future priorities across five core areas: *Health*, *Ambient Air Quality*, *Climate*, *Mobile Sources*, and *Sustainable Transportation, Housing, and Communities*. Building on the 2021 Triennial Strategic Research Plan, it also expands CARB's community-focused approach through two new strategies: 1) a refined public engagement process, and 2) a partnership with community-based organizations (CBOs) to identify research priorities that reflect the needs of underserved and overburdened communities (see Figure 1).

The public engagement process lasted between February and November 2024. The process helped gather input from a wide range of public partners, including California residents, academic partners, environmental justice advocates, private organizations, Tribal members, and others. CARB also distributed surveys to current and former academic contractors, as well as academic and community collaborators, and gathered input at various conferences.

Partnership with the CBOs helped further refine the research priorities so they reflect community concerns and align with CARB's mission, avoid duplicating existing research, are timely, and support current programs with relevant scientific insights. Additional details can be found in *Appendix F - Database of Research Priorities Submitted to CARB for Considerations in the Five-Year Strategic Research Plan*.

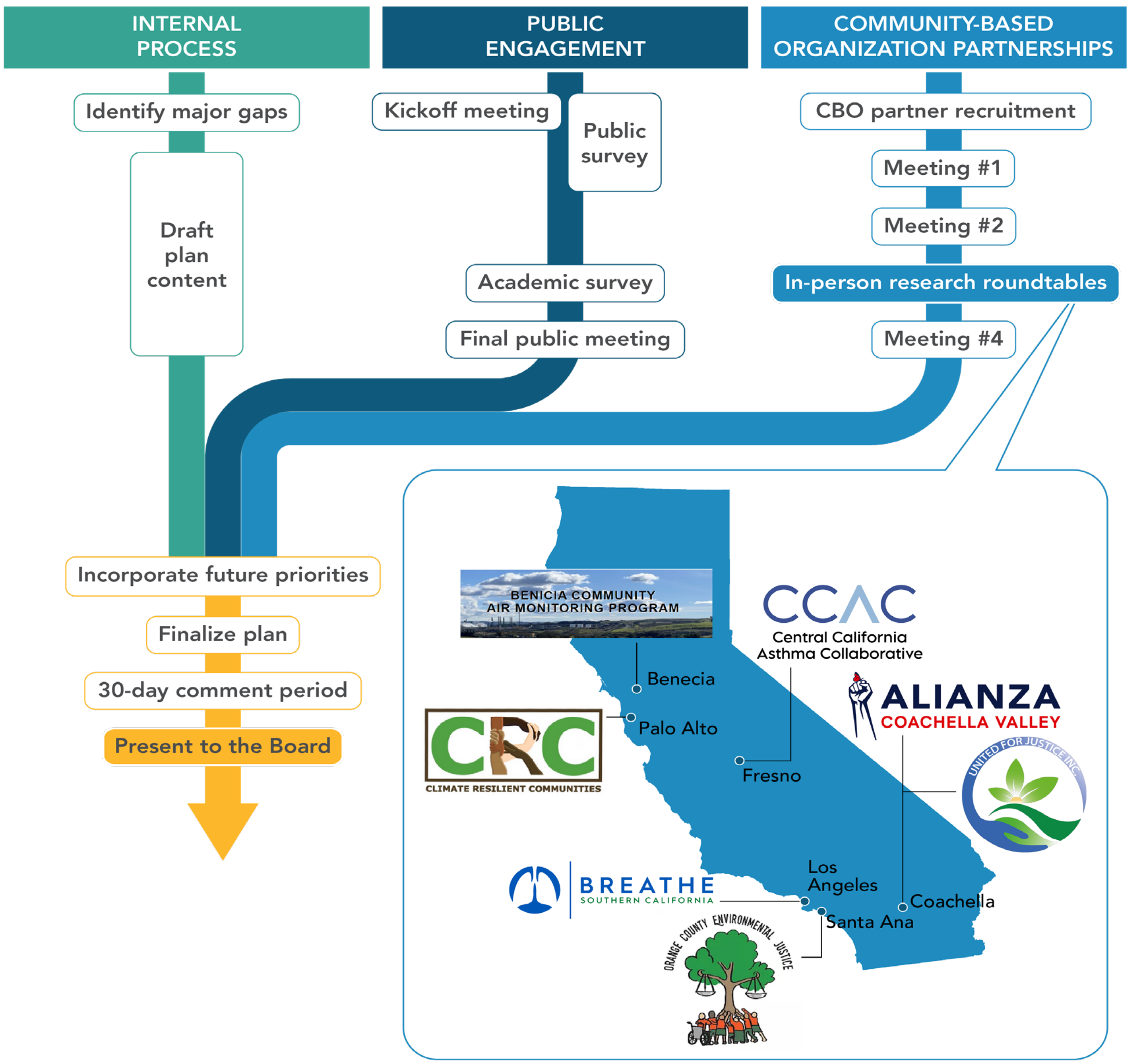

Figure 1: Infographic illustrating the three main processes used to develop this Five-Year Strategic Research Plan.

CARB will continue to collect input on emerging research needs and may issue addenda reflecting public feedback and summarizing selected projects over the five-year term. In addition to supporting internal planning, the Five-Year Plan also serves as a resource for academic, community, and government partners.

Research Program Drivers

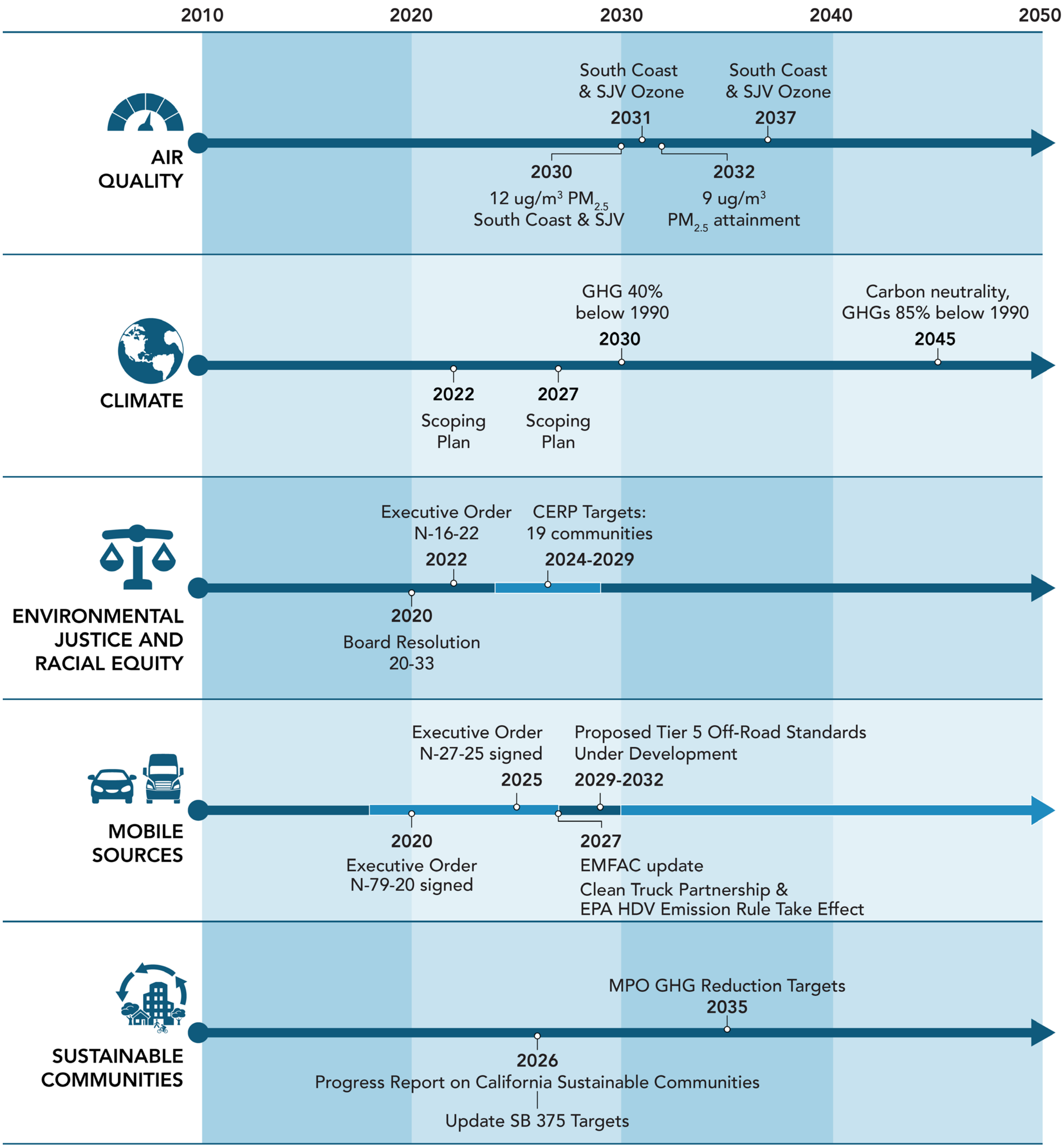

Figure 2: Timeline of major policy drivers in all research areas.

Important regulatory milestones (Figure 2) shape the research priorities presented in this Five-Year Plan. In addition to supporting regulatory needs, CARB's Research Program plays a critical role in identifying emerging air pollution concerns, evaluating scientific questions relevant to achieving CARB's mission, and exploring innovative solutions. The Research Program also aims to evaluate the ongoing impacts and costs associated with air pollution. Key overarching drivers are introduced below.

National Ambient Air Quality Standards

The Five-Year Plan is shaped by the need to comply with the federally mandated *National Ambient Air Quality Standards (NAAQS)* set by the United States Environmental Protection Agency (U.S. EPA). The *Ambient Air Quality Research* chapter addresses the impact of the 2024 revision to the annual PM2.5 standard (lowered to 9 μg/m^3) and outlines research priorities to tackle challenges in new NAAQS non-attainment areas. Ozone and PM non-attainment also remains an ongoing challenge. Multiple areas in California do not meet the NAAQS, and the areas furthest from doing so are in the South Coast region and the San Joaquin Valley. Inaction to address climate change (i.e., warmer temperatures) can exacerbate ozone formation and increase the severity of wildfires, further impacting the state's ability to meet ozone and PM2.5 standards. Continued research on the sources of criteria pollutants and the direct and indirect effects of climate change on air quality is essential for improving air pollution control measures and meeting NAAQS.

Emerging Pollutants and Air Toxics

Air toxics reduction goals are designed to protect the most vulnerable populations from adverse health outcomes of air pollution exposure. CARB's *Air Toxics Program* is critical in reducing exposure to harmful air pollutants throughout California, directly aligning with the state's commitment to improving public health for all Californians. Guided by legislative mandates such as *AB 1807*, *AB 2588*, and *AB 617*, this program aims to reduce exposure to air toxics for all Californians and addresses their disproportionate impacts in overburdened communities.

CARB's recent efforts, such as the $27M *Statewide Mobile Monitoring Initiative*, reflect the agency's emphasis on targeted, community-based solutions. Furthermore, CARB's enhancements to toxic emissions inventory reporting aim to improve the comprehensiveness of the emissions data. The Research Program is also advancing innovative projects, including developing a low-cost, real-time instrument for measuring metals, a regenerative filter for black carbon measurements, and the ongoing studies to quantify cancer risks from air toxics. These initiatives demonstrate CARB's commitment to understanding local sources of air toxics and identifying opportunities that reduce exposure risks. The *Air Toxics* research initiative is outlined in the *Health Research* chapter and discussed in the *Ambient Air Quality Research* chapter.

Carbon Neutrality and Statutory Greenhouse Gas Reduction Mandates

CARB develops strategies for California to meet GHG reduction targets mandated by *Senate Bill (SB) 32*, *Assembly Bill (AB) 32*, and *AB 1279*. The *2022 Scoping Plan for Achieving Carbon Neutrality* lays out a path to achieve targets for carbon neutrality and reduce anthropogenic GHG emissions by 85% below 1990 levels no later than 2045, as directed by *AB 1279*. The Research Program provides valuable insights to inform the development of each Scoping Plan, including qualitative and quantitative health analyses. The outcomes of the Scoping Plan also shape future research priorities. The *Climate Change Mitigation* and *Health Research* chapters detail ongoing research and future research priorities. In addition to the broad air quality improvement and climate change mitigation goals, sector-specific policies drive future reduction strategies for mobile sources, health, and sustainable communities (Figure 2). These sector-specific policy drivers will be discussed further in the various research chapters of this Five-Year Plan.

Environmental Justice and Community Engagement

Despite improvements in air quality over time, disproportionate impacts persist across communities. As part of CARB's efforts to address these disparities, it adopted *Environmental Justice Policies and Actions* in 2001. Subsequently, CARB established the *Community Air Protection Program* (CAPP) under AB 617 that passed in 2017. These initiatives were reinforced by *Resolution 20-33* in 2020. CARB began developing the *Racial Equity Lens* in 2021 to help staff address potential racial equity impacts in CARB's work prior to the release of *Executive Order N-16-22* that directed state agencies to prioritize equity and anti-discrimination efforts. In 2022, CARB released the *Racial Equity Framework* to support staff in implementing these directives. The *Community Engagement Model*, released in 2024, offers a consistent approach to building long-term relationships with communities. Together, these and many other efforts support CARB's actions to reduce emissions and pollution exposure in overburdened communities, while providing funding for community-led air monitoring.[16] CARB also actively engages with the public to provide important updates on CAPP, highlighting meaningful progress made to address local air quality issues within various communities. The most recent update was presented in July 2025.[17]

As part of these efforts, CARB's Research Program has significantly expanded the number of projects involving communities and Tribes as collaborators, advisors, and participants.[18] While not all research projects involve direct community engagement, CARB remains committed to addressing these principles in its research (Figure 3), which is important to help

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[16] *Environmental Justice | California Air Resources Board*.
[17] *OCAP_APR2024_Final.pdf*.
[18] *Environmental Justice in CARB Future Research Priorities | California Air Resources Board*.

shape both research priorities and the methods used to engage communities with the goal of helping close health and opportunity gaps across communities. To support this work, the Research Program has also piloted tools like the *Community Engagement Model* and the *Racial Equity Lens*. Examples of CARB's community-centric research can be found in *Appendix C - Environmental Justice and Racial Equity in CARB Research*. Additional policy drivers for CARB's environmental justice and racial equity are also detailed in *Appendix C.*

Figure 3: This infographic illustrates the ways that CARB has incorporated racial equity and environmental justice into the Research Program since 2021.

Economics

As part of regulatory development, CARB evaluates the costs and benefits of pollution controls, conducting economic impact assessments for many regulations as required by law. In recent years, CARB's incentive programs have begun incorporating behavioral economics in an effort to improve program engagement and effectiveness. The *Health Analysis* research initiative describes how health endpoints can be quantified and monetized to estimate the total costs and benefits of proposed regulations. Similarly, the *Sustainable Transportation, Housing, and Communities Research* chapter examines affordability and economic impacts across socioeconomic groups, especially in relation to housing and transportation. The *Climate Research* chapter introduces new priorities focused on the economic impact of climate change on communities and individuals. CARB's past work on behavioral economics is summarized in the *Triennial Strategic Research Plan*.

Beyond the costs of implementing pollution controls, the costs of inaction are significant. In California, natural disasters such as wildfires are projected to cause up to $131 billion in damages in 2025, with less than half of those losses covered by insurance.[19] Health-related costs linked to wildfire smoke over the past decade have added billions more.[20] At the same time, extreme heat has resulted in approximately $7.7 billion in labor productivity loss over the last ten years.[21] While these figures capture only a portion of the broader impacts of climate change and air pollution, they underscore the importance of proactive mitigation strategies. Continued research to quantify these risks will inform targeted, evidence-based policies that enhance long-term resilience, economic stability, and public health.

Health Analysis

Historically, CARB's health analysis has focused on specific outcomes, such as mortality, asthma emergency room visits, and cardiovascular hospital admissions. However, these measures have underrepresented the broader health effects of air pollution. To address this gap, CARB has recently expanded its health analysis to include additional health outcomes, such as nonfatal acute myocardial infarction (heart attacks), asthma onset, asthma exacerbation, work loss days, lung cancer incidence, and hospitalizations for Alzheimer's and Parkinson's diseases. Ongoing research also investigates air pollution's impact on birth outcomes, metabolic health, and neurological conditions. This broader scope will improve the assessment of health and cost savings from air pollution reduction strategies, health impacts, and costs of inaction. Moving forward, health analysis is expected to include more efforts to expand health outcome data, including disaggregating health data by different groups, examining the cumulative impacts of various pollutants and environmental stressors, and examining climate change vulnerabilities. Refer to the *Health Research* chapter for more information.

Natural and Working Lands

NWLs are important for achieving carbon neutrality and building resilience to the impacts of climate change. The passage of *AB 1757* in 2022 emphasized the need to include nature-based solutions in California's climate efforts, as identified similarly in the *2022 California NWL Climate Smart Strategy* and the State's *2022 Scoping Plan*. AB 1757 directed various agencies to collaborate and set targets for nature-based climate solutions for 2030, 2038, and 2045. Additional research can be used to improve the *California Natural and Working Lands Inventory* and support additional evaluations of existing and potential state-supported conservation, restoration, and management actions. The *Ambient Air Quality Research* and

[19] *Economic Impact of the Los Angeles Wildfires | UCLA Anderson School of Management*.

[20] *Connolly, Rachel, et al. "Mortality attributable to PM2. 5 from wildland fires in California from 2008 to 2018." Science advances 10.23 (2024): eadl1252.*

[21] *Commissioner Lara releases pioneering analysis on hidden costs of extreme heat in California*.

Climate Research chapters include additional information on NWL research, including topics such as agricultural soils and coastal wetlands.

Pesticides

The collaboration between CARB and the California Department of Pesticide Regulation is a key initiative in California's ongoing efforts to address public health, environmental, and climate change concerns. Pesticide emissions, drift, and exposure have been significant public concerns raised in various forums, particularly from agricultural soils. In response, CARB has included research on pesticide emissions and their effect on GHGs as an emerging topic in the Five-Year Plan. This research aligns with broader climate goals, including efforts to reduce GHG emissions from NWLs and climate change mitigation. The *Ambient Air Quality Research* and *Climate Research* chapters include additional information on pesticide research, including work related to agricultural soils, the Healthy Soils Program, and fumigation.

These examples illustrate how CARB research supports state programs and informs national and international efforts. Additional research highlights and examples of policy-relevant findings are included throughout the Five-Year Plan, particularly in each chapter's background and research highlights sections.

What Types of Research Does the California Air Resources Board Do?

CARB does research in various ways, including in-house research, external research contracts, collaborative efforts, and funds community-driven projects. CARB also coordinates research with other state agencies, federal agencies, local air districts, and research institutions to avoid duplication of effort, leverage funding, identify opportunities, share lessons learned, and maximize the utility and applicability of research results. These collaborations facilitate interdisciplinary knowledge exchange on the latest technological advances, measurement results, and external regulatory activities.

In-house Research

CARB staff collect original data, leverage data from externally funded research contracts, perform analysis, write white papers and peer-reviewed publications, and develop new tools and models. A list of in-house research projects is provided in *Appendix D – In-House Research Projects.* A list of CARB-authored peer-reviewed publications is provided in *Appendix E - Impact of CARB Research Program work in the literature*.

External Research Contracts

For external contracts, CARB considers the expertise in the Universities of California and California State Universities first, per the *California Code, Health and Safety Code section*

39704. Researchers from the Universities of California and California State Universities can subcontract with members of other public and private institutions, such as other universities, non-profit organizations, community-based organizations, or private research institutes. In some cases, projects are funded through a competitive bid process. Research contracts last one to three years. When results are available, they are shared publicly and incorporated into programs.

Who Reviews Projects to Ensure Scientific Rigor?

Draft proposals and Draft Final Reports are reviewed by the *Research Screening Committee* (RSC) in public meetings. The Board's legislatively mandated RSC consists of scientists, engineers, and others knowledgeable, technically qualified, and experienced in air pollution problems. CARB regularly recruits new RSC members and encourages the public to submit nominations.[22]

How Are Project Updates and Results Shared?

Each research contract has a webpage accessible from CARB's *active contract page*. In some cases, community engagement is a key aspect of public participation throughout the contract. In most cases, project results are not shared until the project is near completion. Upon completion, a final report is posted to the project's contract page along with a plain-language summary. Often, the contractor presents the results in a public seminar. Seminar announcements are distributed through *CARB's listserv* and posted to *CARB's main events calendar*. The contract page may also include recordings of the seminar and links to any tools or databases created through the contract. A list of proposed research projects for fiscal years 2024-2025 and 2025-2026 can be found in *Appendix A*. A full list of completed research contracts since the last Strategic Plan is found in *Appendix B – Recent Research Final Reports: March 2021 - Present.* A *research contract search tool* is also available online.

As scientific findings are often useful beyond California's borders, CARB endeavors to provide summaries to not just the public but to other jurisdictions to support their programs. To improve accessibility and strengthen outreach to a broad range of audiences, the Research Program has begun providing brief, plain-language summaries of research objectives and key findings, both before and after project completion.

[22] *RSC New Member Selection Process | California Air Resources Board*.

Chapter 1: Health Research

A. Introduction

The California Air Resources Board (CARB) develops regulations and policies to achieve ambient air quality standards, reduce greenhouse gas (GHG) emissions, lower cancer risk from air toxics, and decrease exposures in communities disproportionately impacted by multiple air quality challenges. These efforts are intended to deliver public health, environmental, and economic co-benefits for all Californians.

To support this work, CARB's health research informs health analysis tools used to evaluate the health impacts and benefits of air pollution reduction programs and proposed regulations. This research also advances understanding of the links between climate and health, helps identify sources of air pollution, evaluates associated health impacts, and assesses the costs of inaction. The studies described below inform the scientific foundation for CARB's policy decisions and offer valuable insights that can inform similar initiatives in other jurisdictions.

How is Health Research Used at the California Air Resources Board?

CARB's health research supports a range of important outcomes that inform policy and advance public health protection. These include:

- Identifying new populations of concern, such as pregnant individuals and their children, who may be especially vulnerable to air pollution exposure.
- Examining differences in air pollution impacts across communities to help reduce health disparities and improve resilience.
- Demonstrating the health benefits of CARB's regulations through the evaluation of new or expanded health endpoints.
- Developing methodologies and tools to quantify the health impacts and co-benefits of air quality regulations.
- Strengthening the scientific evidence base on the public health impacts of air pollution.
- Advancing qualitative and quantitative methods to evaluate the health benefits of climate change mitigation strategies.
- Enhancing understanding of the public health costs associated with inaction on air pollution and climate change.

B. Health Impacts of Climate Change and Wildfire Smoke

Climate change already affects Californians through more frequent and severe wildfires, extreme heat, and prolonged drought. It poses direct health risks, including increased heat-related illnesses, injuries, and deaths from extreme weather events such as severe storms, flooding, and wildfires. Indirect health impacts include worsening respiratory and cardiovascular diseases due to air pollution, the spread of vector-borne and fungal illnesses, reduced food security, and growing mental health challenges. As these impacts continue to intensify, California's research in this area can also offer valuable insights to inform climate change mitigation and public health strategies in other states.

Past Research

CARB's Research Program has performed both qualitative and quantitative analyses to evaluate the health benefits of climate action.[23] The qualitative analysis assessed the potential health benefits of reducing fossil fuel use alongside healthier ecosystem management. Key focus areas included heat-related impacts, children's health and development, economic and food security, mobility and physical activity, urban greening, wildfires and smoke exposure, and housing affordability. This analysis reviewed existing scientific evidence on major health outcomes and, where possible, evaluated the magnitude and direction of these effects, capturing both positive and negative associations between environmental exposure and health outcomes.

Current Research

Hotter and drier conditions driven by climate change are contributing to larger, longer-lasting wildfires in California. These wildfires emit significant amounts of criteria pollutants, air toxics, and GHGs, exacerbating the health impacts associated with fine particulate matter (PM2.5) exposure. CARB has funded research[24] to estimate the statewide health impacts of wildfire smoke and to inform smoke management programs. This work is being conducted in collaboration with community partners to incorporate local needs and priorities.

CARB is also advancing the estimation of health benefits associated with nature-based climate strategies. One ongoing project[25] is quantifying the health benefits of nature-based management scenarios at a finer spatial scale while incorporating additional health endpoints. Another project is focused on assessing the regional health benefits of greenness, such as trees, forests, and gardens, across California.

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[23] CARB Contracts *19RD015* and *19RD006*.
[24] CARB Contract *21RD003*.
[25] CARB Contract *23RD004*.

Climate stressors such as wildfires, air pollution, and extreme heat are often examined individually but frequently occur simultaneously, potentially causing greater harm to health, especially among vulnerable populations. To address this, CARB is funding a project[26] that aims to estimate the combined effects of multiple climate stressors and their health impacts across vulnerable communities in various regions of California. Such work is important for understanding the costs of inaction. It can also support CARB in quantifying the comprehensive health co-benefits of reducing GHG emissions while identifying effective strategies to protect vulnerable populations.

Future Research Needs

Timely Drivers

Climate change is one of the greatest global public health threats, and addressing it presents a powerful opportunity to improve health outcomes.[27, 28] CARB supports research on the health benefits of climate mitigation action, including nature-based strategies. Under *AB 1757* (Garcia, Stats. of 2022, Ch. 341), CARB and partner agencies are tasked with setting targets and quantifying both emissions reductions and associated health co-benefits of nature-based climate solutions in the Natural and Working Lands (NWL) sector.

Wildfire risk is a growing concern, especially for communities located in the wildland-urban interface (WUI). Populations in these areas face heightened exposure to toxic pollutants released from burning buildings and vehicles. These health risks during wildfire events are linked to a broad range of air toxic emissions. The impacts of wildfires extend beyond California, and research in this area can provide valuable insights applicable to other states. For more details, see the *Wildfire Emissions in a Changing World and Impacts on Environmental Justice Outcomes* section.

[26] CARB Contract *23RD005*.

[27] *Romanello, Marina, et al. "The 2021 report of the Lancet Countdown on health and climate change: code red for a healthy future." The Lancet 398.10311 (2021): 1619-1662.*

[28] *Watts, Nick, et al. "Health and climate change: policy responses to protect public health." The lancet 386.10006 (2015): 1861-1914.*

Future Research Priorities

- What are the co-benefits of climate adaptation and mitigation strategies in California when examined at a finer geographic and demographic scale?
- What economic, air quality, health, and other co-benefits of climate mitigation action remain underrepresented in current assessments, particularly for Tribal communities and populations in WUI areas?
- What tools and analytical approaches can be developed to help understand how climate change affects people's health, both now and in the future, to help inform communities and strengthen their resilience?

- What are the physical and mental health impacts of exposure to smoke and ash from wildfires, WUI fires, and prescribed burning events?
- How do these health effects differ between long-term or chronic exposures to multiple fires over several years (e.g., lasting effects) and short-term peak exposures (e.g., acute effects)?
- In what ways do wildfire smoke exposures interact with existing poor air quality to worsen adverse health outcomes?
- What are the most effective strategies for communicating these health risks to the public, including guidance on risk management?
- How can we best evaluate the effectiveness of health protective measures implemented during wildfire events?

- Are smoke and ash from wildfires and WUI fires more toxic than emissions from other sources of air pollution?
- What are the effects of smoke and ash on indoor air quality, and which filtration methods, tools, and guidance can be most equitably deployed to protect priority communities, especially those living in WUI areas?

- What are the quantitative and qualitative health impacts of extreme weather events, such as heat waves, droughts, and floods?
- How can we support climate adaptation programs to effectively achieve health co-benefits?

- What are the most significant public health risks, including acute and long-term health outcomes, associated with climate change events and multi-pollutant exposure, including air toxics?
- Which populations and geographic areas are most at risk?
- What tools and methodologies can be used to map overlapping risk factors and health outcomes related to climate change impacts?
- What are the epigenetic effects of these exposures, including potential impacts across multiple generations?
- What strategies are effective in closing health disparities linked to these risks?

C. Indoor Health Pollution Sources, Exposure, and Mitigation

Indoor air pollution consistently ranks among the top environmental health risks identified by state and federal agencies.[29] This is partly due to the fact that Californians spend an average of 87% of their time indoors, where exposure to air pollutants can be significant.[30] In response, CARB has invested in research to identify pollution sources, evaluate exposure reduction strategies, and develop innovative approaches to engage and inform the public.

Past Research

The 2005 CARB report on indoor air pollution[31] prompted further research that led to *CARB's Indoor Air Cleaning Devices regulation*, which limited ozone emissions from these devices. More recently, CARB funded a white paper[32] evaluating air cleaners with electronic technologies for ozone, formaldehyde, and ultrafine particles. CARB has also funded studies examining air quality in multifamily units[33] and filtration in schools.[34] With the increased use of such devices during the COVID-19 pandemic and rising wildfire smoke events, understanding the science behind their health protection capabilities has become even more

[29] *Johnson, Barry L. "A review of health-based comparative risk assessments in the United States." Reviews on Environmental Health 15.3 (2000): 273-288.*

[30] *Jenkins, Peggy L., et al. "Activity patterns of Californians: use of and proximity to indoor pollutant sources." Atmospheric Environment. Part A. General Topics 26.12 (1992): 2141-2148.*

[31] *Indoor Air Quality in California - A Report to the Legislature*.

[32] CARB Contract *22RD003*.

[33] CARB Contract *19RD013*.

[34] CARB Contract *20RD015*.

important. California's list of certified air cleaners under the *Air Cleaner Regulation* now serves as a national resource.

Current Research

CARB continues to advance understanding of indoor air pollutant control strategies in California. Since the *2005 Indoor Air Pollution Report*, new challenges such as climate change and wildfire smoke have emerged. A current study[35] is updating the report to identify priority indoor pollutants, their health impacts, and effective strategies to reduce exposure. The findings can guide CARB and other agencies in improving indoor air quality (IAQ), with potential applications beyond California, particularly for mitigating exposures to common indoor air contaminants.

CARB's indoor exposure mitigation research also prioritizes communities facing challenges in achieving healthier IAQ. One study[36] evaluated low-cost sensors and provided practical recommendations to help individuals reduce their exposure and make informed decisions.[37, 38]

Future Research Needs

Timely Drivers

In 2020, CARB provided the Board with an update on the *California Indoor Air Quality Program*. *Board Resolution 20-32* directed staff to support updates to the California *Building Standards Code*, including the following priorities:

- Improve ventilation and promote electrification of appliances.
- Support the development of rules and best practices to reduce emissions from appliances.
- Expand efforts to understand disparities in indoor air quality and enhance community engagement on these issues.
- Develop indoor air quality guidance documents to educate the public on health-protective actions, including during extreme events such as wildfires or other large-scale outdoor air pollutant incidents.

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35 CARB Contract *22RD026*.

36 CARB Contract *22RD020*.

37 Ofodile J. and Ivey C. E. (2025). Low-Cost Sensors for Healthier Indoor Air Quality in Impacted Communities. California Air Resources Board.

38 *Reducing Your Exposure to Indoor Air Pollution | California Air Resources Board*.

These Board mandates will drive future research priorities in the *California Indoor Air Quality Program*, which will continue to focus on evaluating the effectiveness of mitigation strategies and quantifying their health impacts.

Future Research Priorities

- What are the indoor air quality benefits of building decarbonization, particularly for overburdened communities?
- How effective are different building decarbonization strategies in reducing indoor air quality disparities and associated health impacts?
- What tools and metrics can be used to track and quantify disparities in indoor air quality as building decarbonization efforts progress?

- What are the most effective strategies, such as educational outreach, guidance documents, and incentive programs, for promoting the adoption of tools and mitigation measures that protect indoor health, especially among vulnerable populations?

- What additional technologies or recommendations, whether behavioral, operational, or related to building management, can improve indoor air quality in high-risk settings such as schools, residential buildings, elder care facilities, and correctional institutions?

- What current or emerging methodologies can be utilized or developed to quantify the health impacts and burdens associated with indoor air pollutant exposures in both residential and non-residential settings?

- What are the most effective communication strategies for promoting the use of indoor air guidelines across residential, commercial, and industrial settings?
- What updates are needed to strengthen existing indoor air quality guidelines?
- Are additional or specialized guidelines needed to address indoor air quality during extreme events, such as wildfires?

Research Highlight: Asthma in Communities near Port & Rail Operations

What was found?

10%

Estimated increase in medication use per 10 μg/m^3 of PM2.5 increase from port and rail operations

~3x

Medication use increase from port and rail operations exposures in under-resourced communities compared to other communities.

Why is this work important?

- Confirms communities near PRO are more burdened by air pollution exposure and health impacts.
- Supports CARB's regulations & policies to reduce emissions from port and rail operations and goods movement that particularly impact under-resourced communities.

The movement of goods through port and rail operations is a large source of air pollution exposure. A **CARB project** looked at the impacts of port and rail operations pollution on asthma and emergency hospital visits in Southern California communities, including under-resourced communities near Los Angeles, Ventura, San Bernardino, Orange, Riverside, San Diego, and Imperial counties.

D. Health Analysis: Expanding Understanding of Health Outcomes and Environmental Justice Factors

As directed by *Resolution 20-13*, CARB continues to expand its health analysis tools to capture a broader range of benefits associated with air pollution reductions.[39] When quantification is not feasible, CARB conducts qualitative evaluations based on the best available scientific literature. These assessments help identify health impacts, source-specific effects, and additional outcomes extending beyond the standard health endpoints in Table 1. CARB also plans to incorporate health effect estimates from recent CARB-sponsored research to strengthen its health analysis further.

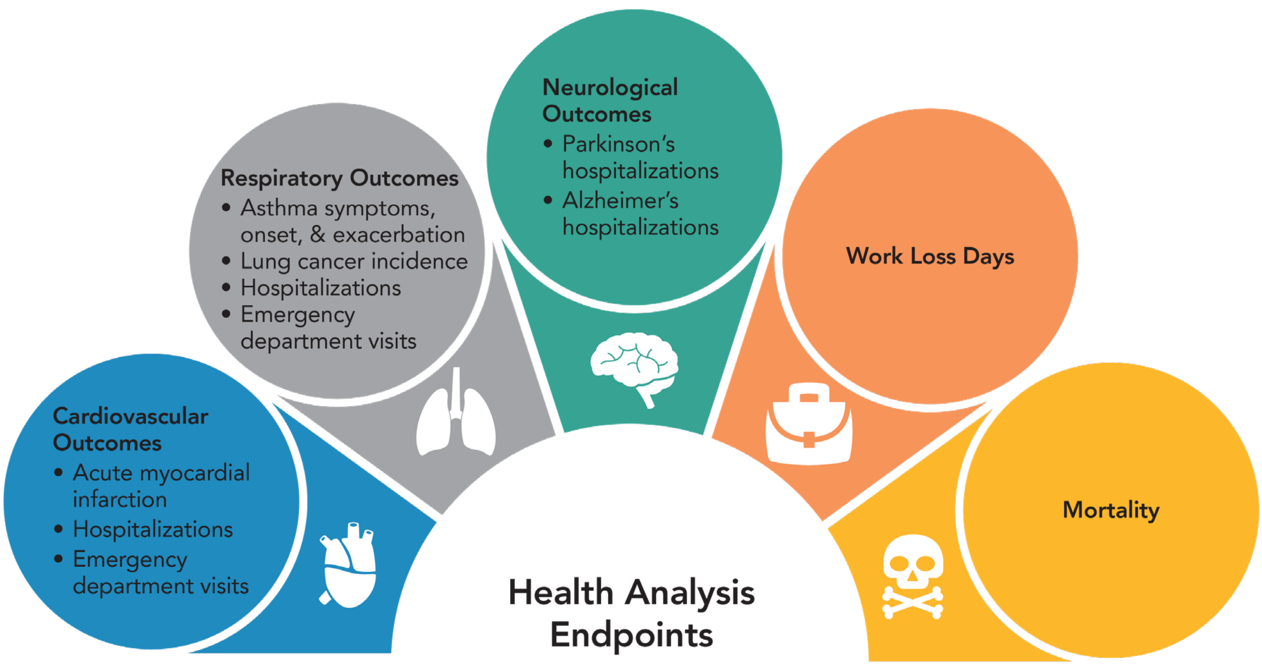

Figure 4: Illustration of health analysis endpoints.

Table 1: Previous and current PM2.5 health endpoints in CARB's health analysis methodology. ED = emergency department. *CARB previously calculated this health endpoint but has updated the effect estimate based on more recent research findings. **CARB initially calculated ED visits for asthma only; this endpoint has been expanded to include all respiratory diseases.

Previous Set of Endpoints	Mortality Cardiovascular hospital admissions*

[39] *California Air Resources Board Updated Health Endpoints Bulletin - Edited Nov 2022_0.pdf*.

	Respiratory hospital admissions* Asthma ED visits**
Current Set of Endpoints	Mortality Cardiovascular hospital admissions Respiratory hospital admissions Respiratory ED visits Cardiovascular ED visits Acute Myocardial Infarction, Nonfatal Asthma Onset Asthma Symptoms / Exacerbation Work Loss Days Lung Cancer Incidence Hospitalizations for Alzheimer's Disease Hospitalizations for Parkinson's Disease

Past Research

CARB estimates the health benefits of emission reductions resulting from its programs, regulations, and policies. Historically, only a limited number of health effects were assessed. However, growing scientific evidence has established strong links between PM2.5 exposure and a broader range of adverse health outcomes.[40] In November 2022, following a public process, CARB expanded the list of PM2.5-related health endpoints included in its routine health assessments. The updated list continues to include premature mortality, along with multiple cardiovascular, respiratory, and neurological endpoints (see Table 1). Although developed for California, these endpoints may also be useful to other states in designing and evaluating air pollution reduction strategies.

Evaluating and quantifying additional health endpoints helps CARB better understand the broader health benefits of its policies and programs, the economic burden of air pollution-related illnesses and healthcare costs, and the disparities in health outcomes across different communities. Gaining a clearer picture of the health impacts associated with the status quo further underscores the urgency and importance of avoiding inaction.

Current Research

Current research is investigating the effect of PM2.5 exposure on additional health outcomes, with particular focus on children and seniors. One study[41] is examining associations with preterm birth, low birth weight, autism spectrum disorder, and neurodegenerative conditions such as Parkinson's Disease, Alzheimer's Disease, and cognitive decline. Another ongoing

[40] Some examples include CARB Contracts *20RD016*, *19RD006*, and *19RD004*.
[41] CARB Contract *21RD004*.

study[42] focuses on children's neurodevelopment, assessing cognition, mood, attention, and behavior. A third project[43] explores metabolic outcomes, including diabetes. These studies are expected to yield significant health impact estimates with important economic implications and relevance beyond California.

In parallel, research is expanding to better understand how air pollution contributes to health disparities, particularly among different racial and ethnic groups. A recent white paper[44] reviewed existing research on this topic and prompted CARB to collaborate with academic experts to integrate these insights into future health analyses. Additionally, CARB is initiating a project to develop a framework aimed at improving health assessment for communities most burdened by air pollution and other environmental stressors. Findings from these efforts can help more accurately evaluate the benefits of future regulations and programs for California's most impacted populations.

Future Research Needs

Timely Drivers

Resolution 20-13 directs CARB staff to develop new quantitative and qualitative approaches to assess the health benefits of the agency's regulatory actions and programs. It also calls for new approaches to evaluate and communicate the health benefits of reducing GHGs and improving community sustainability, resiliency, and quality of life. Achieving these goals will require advanced health research and is expected to drive CARB's research priorities for the next five years.

[42] CARB Contract *22RD005*.
[43] CARB Contract *22RD010*.
[44] CARB Contract *22RD025*.

Future Research Priorities

- How can we evaluate and, where possible, quantify cumulative health impacts from multiple air pollution sources alongside community and environmental stressors at the local level?
- Which communities and Tribal populations bear the greatest burden from these cumulative exposures
- What are the most important air pollution sources contributing to these health burdens?
- Which climate change-related impacts exacerbate these cumulative health burdens?

- How do cumulative health burdens differ when influenced by low-level, chronic exposures compared to acute, high-exposure events?
- What are the health effects associated with lower-level exposures, and how might those vary depending on the air pollution sources involved?

- How can health analysis tools be developed or expanded to provide more spatially resolved information on exposures and the health benefits of emissions reductions?
- What methodological approaches can be explored to better assess and address cumulative environmental and health burdens?

- Which additional health metrics and endpoints should be studied to better assess the impact of air pollution and climate change on public health?
- What are the projected health consequences of inaction on climate change?

- How can longitudinal studies be leveraged to assess the long-term health benefits of CARB's air pollution reduction efforts?

E. Air Toxics

Air toxics are chemical pollutants in the air that may cause or contribute to serious illness or death, either immediately or over time. CARB has several programs to regulate toxic compounds associated with serious health risks. Many air toxics have been designated as Toxic Air Contaminants (TAC) by CARB through an established identification process under *AB 1807* (Tanner, Stats. of 1983, Ch. 1047) or have been classified as a hazardous air pollutant by the U.S. EPA. Once a substance is designated as a TAC, CARB can initiate the development of air toxic control measures (ATCMs) to reduce or eliminate emissions from sources across the state.

At the community level, particularly in overburdened areas and *AB 617 communities*, CARB supports efforts to reduce exposure through enhanced community air monitoring, development of emissions reduction plans, and funding through community air grants.

Past Research

In the past, CARB-funded research has supported the evaluation of health impacts from exposure to specific air toxics, such as hexavalent chromium from chrome plating operations and formaldehyde from composite wood consumer products.[45] More recent efforts have expanded to include emerging contaminants and community-driven concerns.[46] For example, a community engagement project[47] in the Salton Sea region highlighted residents' concerns about exposure to hydrogen sulfide and other airborne pollutants.

Current Research

CARB implements a wide range of regulations and programs to control air toxics such as diesel particulate matter (DPM), benzene, hexavalent chromium, lead, and others. For example, CARB has adopted rules to reduce DPM exposure from commercial harbor craft[48] and to limit emissions from localized sources of air toxics, including chrome plating operations.[49] While CARB estimates cancer risk reductions resulting from these efforts, it does not yet have a method to quantify those benefits in monetary terms.

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[45] CARB Contract *93-315*.

[46] CARB Contract *21RD004*.

[47] *Salton Sea Community Webinars | California Air Resources Board*.

[48] CARB Health Analyses (2021). *Proposed Amendments to the Commercial Harbor Craft Regulation*.

[49] CARB Health Risk Assessment (HRA), *The Proposed Amendments to the Airborne Toxic Control Measure for Chromium Electroplating and Chromic Acid Anodizing Operations*.

Ongoing research[50] focused on developing valuation methods for cancer-related health impacts, incorporating both direct and indirect costs and disaggregating findings by race and ethnicity. These efforts can enable more comprehensive benefits assessments in California and provide valuable insights for other jurisdictions pursuing air toxics reduction strategies.

Future Research Needs

Timely Drivers

Current policies and programs targeting air toxics continue to shape CARB's future research priorities. The foundational *AB 1807*, the Toxic Air Contaminant Identification and Control Act, was created in 1983 to reduce exposure to air toxics through TAC identification and ATCM development. The *Air Toxics Hot Spots program* was enacted in 1987 and requires facilities to report the types and quantities of certain toxic substances routinely released into the air. The program aims to protect public health by collecting emissions data, identifying facilities with potential for localized impacts, and requiring those that pose a significant risk to implement measures that reduce their emissions below the threshold of significance. Other policy drivers include:

- *Board Resolution 23-16* on hexavalent chromium from the chrome plating industry.
- The *Community Air Protection Program*, which requires quantifiable air pollution emission reductions in environmental justice communities, including reductions in air toxics.
- The *Emission Inventory Criteria and Guidelines Regulation (EICG)*, which sets forth emissions reporting requirements and guidelines for reporting toxic substance releases pursuant to *AB 2588* (Connelly, Stats. 1987), and the *Criteria Air Pollutants and Toxic Air Contaminants Reporting (CTR) Regulation* pursuant to AB 617 (Garcia, Stats. of 2017, Ch. 136).
- The *Consumer Products Program*, which aims to reduce the amount of volatile organic compounds (VOCs), TACs, and GHGs that are emitted from using chemically formulated consumer products.

In addition, CARB has developed the *California Air Toxics Assessment (CATA)*, a tool that integrates emission inventories, meteorological data, and Inhalation Unit Risk Factors (IUR) to model, calculate, and map cancer risk from air toxics and associated emission sources across California.

[50] CARB Contract *23RD003*.

Future Research Priorities

Future research will aim to address knowledge and information gaps related to air toxics exposure, health impacts, and associated data needs. Priority areas may include community-level air toxics exposure and health studies, as well as the development of improved source testing methods. Future research will prioritize supporting CARB tools (e.g., CATA), informing regulatory actions including ATCMs, building decarbonization strategies, and other plans and policies. Additional studies may evaluate the use of alternative chemicals and quantify the health and economic costs of inaction. Research in these areas supports California's goals and may apply to other regions with similar air toxics challenges.

- How do specific air toxics and their emission sources influence community-level exposures and health outcomes?
- What is the most current scientific understanding of health values for established and emerging air toxics?
- What alternative methods can be used to assess the toxicity of air toxics when traditional data are limited or unavailable?
- What advancements can be made in source testing techniques to better characterize emissions of new and emerging air toxics?

- How can decarbonization strategies contribute to reductions in air toxic exposures, and what are the associated health benefits?
- How does the adoption of alternative chemicals or technologies influence health risks related to specific sources or activities involving air toxics?
- How effective are current ATCMs in reducing air toxics exposures and their health impacts?
- What novel methods, such as analysis and valuation of reduced cancer risks, can be developed to improve the assessment of air toxics risk reduction strategies?

F. Community-level Exposures and Disparities

Reducing emissions and addressing air quality disparities are key priorities for CARB. This effort includes strengthening internal capacity to engage communities effectively and support inclusive, collaborative decision-making. Building community capacity and actively involving residents in research and outreach are essential to achieving meaningful environmental and health outcomes across California.

Exposure to air pollution and its associated health impacts are not experienced equally across the state. Low-income communities and communities of color, including Black, Latino, and Indigenous populations, consistently experience significantly higher levels of pollution and related health risks. These communities also tend to have lower resilience to climate impacts due to limited resources and reduced access to mitigating factors such as green space.

Past Research

CARB has conducted numerous research projects to better understand community-level exposures and their associated health impacts. The passage of AB 617 further encouraged the development of systematic methods to quantify exposures and assess certain activities that may impose health burdens in vulnerable communities.[51] With national tools such as the U.S. EPA's Environmental Justice Screening and Mapping Tool (EJSCREEN)[52] no longer available, ongoing research to enhance and support California's environmental justice efforts will become increasingly important and may serve as a model for other jurisdictions.

Current Research

CARB studies have identified disparities in exposure to air pollution and noise across communities. However, more data is needed to understand how specific sources, activities, and living environments influence individual exposure levels. The San Joaquin Valley Pollution and Health Environment Research (SPHERE) study[53] is addressing this gap by using indoor and outdoor air monitoring and personal exposure data to assess air pollutants and noise exposures in the Stockton and Fresno areas. The findings can offer insights into how personal behaviors and external factors contribute to exposure and IAQ.

In addition, CARB funded CalHealthMap,[54] a statewide health tracking dashboard hosted by UCLA. Developed in response to community concerns, the dashboard provides zip-code level data on respiratory, cardiovascular, metabolic, and birth outcomes and premature mortality.

Future Research Needs

Timely Drivers

CARB's Research Program will continue to support the *Community Air Protection Program (CAPP)*, particularly where studies can propose actionable strategies to reduce exposures. *The Health Appendix of the Scoping Plan* emphasizes the importance of helping communities

[51] CARB Contract *17RD035*.
[52] CARB Contract *11-336*.
[53] CARB Contract *20RD012*.
[54] CARB Contract *21RD005*.

reduce environmental hazards and address social determinants of health to build resilience to climate threats. Additional research can help further understand the expected co-benefits of implementing these strategies.

Board Resolution 20-13 also directs CARB to develop new methods for evaluating health impacts in disadvantaged communities, recognizing their greater exposure and vulnerability. Tools like *CalEnviroScreen* and other studies have demonstrated that race and income are significant predictors of pollution burden and health disparities. Ongoing research will help refine tools, track outcomes, and support more effective and equitable strategies.

While grounded in California policies, this research also offers valuable insights for other states facing similar environmental justice and public health challenges.

Future Research Priorities

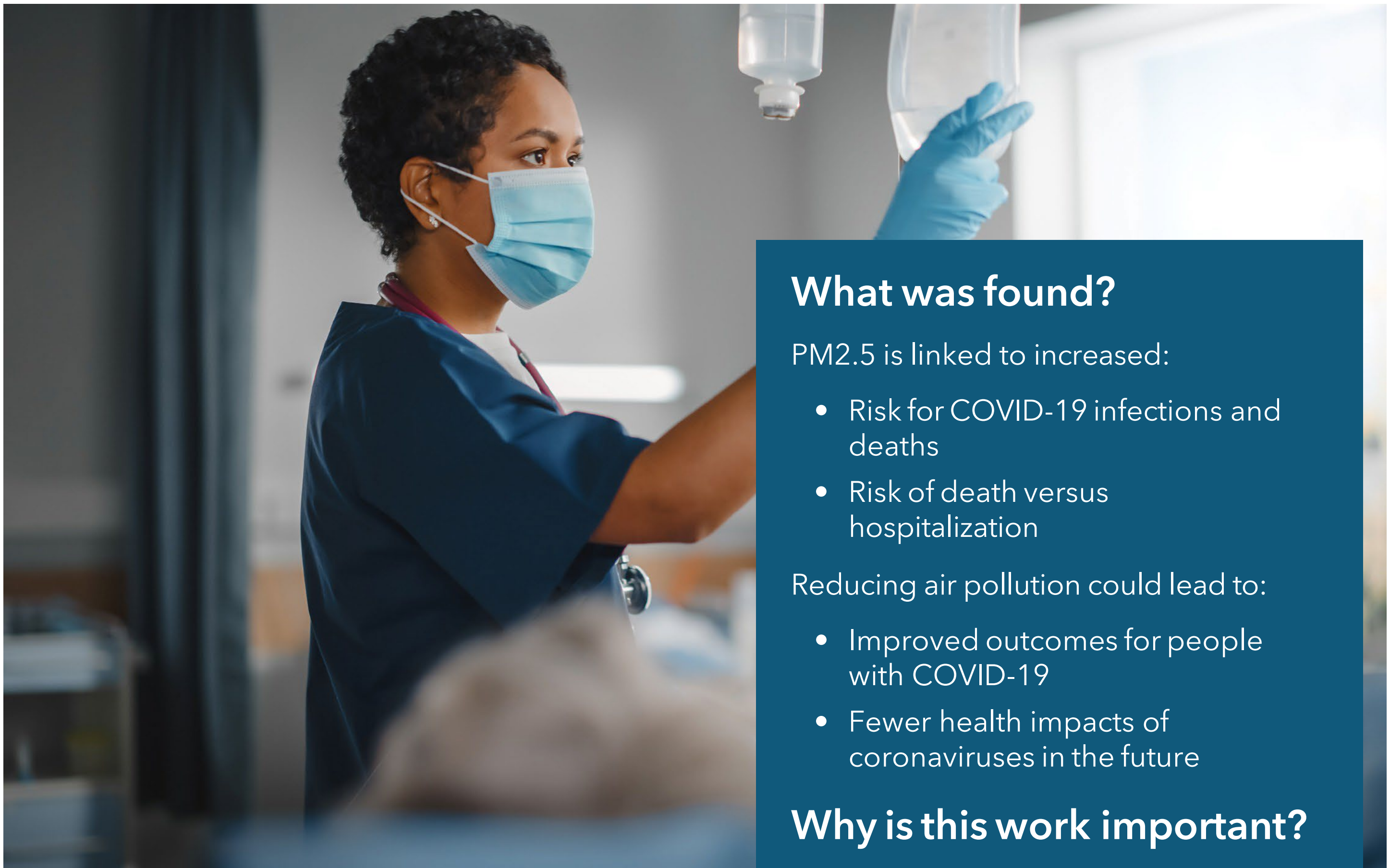
- How do socioeconomic factors influence air quality and related health outcomes within communities?
- Can retrospective analyses help reveal how air quality disparities have changed over time, identifying where conditions have improved and where disparities persist?

- Which communities are most at risk from combined exposures to multiple pollutants and the impacts of climate change?
- What unique pollutant mixtures and associated health outcomes affect communities near multiple stationary and mobile emission sources?

- How can we evaluate air pollution and related health outcomes systemically at finer spatial resolution?
- What methods can be used to track progress in reducing environmental health disparities over time?
- What data can support reliable air quality modeling and exposure assessment at localized scales?

- What are the acute and chronic health impacts of exposure to air toxics and dust from areas such as the Salton Sea?
- How effective are various mitigation measures in reducing these exposures and associated health risks?

Research Highlight: How is Air Pollution Connected to COVID Risk?



Over 4,000 COVID deaths could have been prevented over the timespan of a year if all of California had met federal air quality standards for **PM2.5 pollution**. Two CARB projects looked at the impact of exposure to air pollution on COVID-19 health outcomes in California. One project looked at data across the **entire state** of California and the other focused on **Southern California**.

What was found?

PM2.5 is linked to increased:

- Risk for COVID-19 infections and deaths
- Risk of death versus hospitalization

Reducing air pollution could lead to:

- Improved outcomes for people with COVID-19
- Fewer health impacts of coronaviruses in the future

Why is this work important?

People living in high PM2.5 exposure areas are more likely to:

- Be people of color
- Low-income neighborhoods
- Experience worse COVID-19 outcomes

This adds evidence to a large amount of research linking long- term air pollution exposure to negative respiratory effects, including viral infections. California must reduce air pollution levels to protect public health and save lives, especially for priority communities.


2017-11-20 00:06:02
PM2.5
92
µg/m³
UNHEALTHY
35 75 115 150 250
19℃
64%

Chapter 2: Ambient Air Quality Research

A. Introduction

CARB's ambient air quality research supports regulatory mandates and public health goals by informing the *State Implementation Plan (SIP)*, advancing the *Community Air Protection Program (CAPP)* under *Assembly Bill (AB) 617*, and addressing emerging ambient air quality challenges. This work aims to improve understanding of air pollution sources, exposure risks, and effective mitigation strategies.

To comply with the federal Clean Air Act, California must meet the *National Ambient Air Quality Standards (NAAQS)* set by the U.S. EPA. For regions not in compliance, states are required to develop SIPs detailing how they will achieve and maintain attainment. Currently, the San Joaquin Valley (SJV) and the South Coast Air Basin (SoCAB) remain in non-attainment for ozone and fine particulate matter (PM2.5).[55] The recently lowered annual PM2.5 NAAQS standard (9 μg/m^3 in 2024) is expected to increase the number of non-attainment areas.[56] Research on air pollutant levels, chemical composition, and emission sources is important for the development of SIP, especially in the context of increasing wildfire impacts.

The objectives of AB 617 are important considerations for addressing ambient air quality disparities in disadvantaged communities (DAC) throughout the state. The development of the *Community Air Monitoring Plan (CAMP)* and Community Emission Reduction Plans (CERP) can benefit from access to air quality data and screening tools. These research products are especially helpful in DACs lacking regulatory monitors. While CARB emission databases like *California's Emissions Inventory Data Analysis and Reporting System (CEIDARS)* have enhanced inventory reporting under *AB 2588*, gaps remain, particularly for volatile organic compounds (VOCs). Recent field measurements revealed discrepancies between inventory estimates and real-world emissions from biogenic sources and volatile chemical products, highlighting the importance of comprehensive monitoring and community engagement to gather additional evidence of poor air quality.[57] Exposure to air toxics (gases and trace metals), black carbon particles, and ultrafine particles (UFP) also remains a health concern, particularly in overburdened communities.

This research supports California's air quality goals and provides insights that can inform national and international air quality strategies.

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[55] *Ambient Air Quality Standards Designation Tool | California Air Resources Board*.

[56] *SIPs for the 9 μg/m3 PM2.5 Standard | California Air Resources Board*.

[57] *Pfannerstill, Eva Y., et al. "Comparison between spatially resolved airborne flux measurements and emission inventories of volatile organic compounds in Los Angeles." Environmental Science & Technology 57.41 (2023): 15533-15545.*

How is Ambient Air Quality Research Used at the California Air Resources Board?

State Implementation Plan

CARB's Research Program supports SIP development by gathering and analyzing detailed atmospheric data to better characterize air quality across California. This includes deploying advanced equipment at key locations such as Fresno-Garland and Bakersfield-California Avenue Supersites. In addition, CARB also collaborates with the *Atmospheric Science and Chemistry mEasurement NeTwork (ASCENT)* to expand PM2.5 speciation monitoring capabilities in the SoCAB. These advanced tools offer more chemically and temporally detailed data than standard regulatory air monitors. This enhanced resolution helps evaluate air pollution trends, identify sources using speciation and source apportionment techniques, and inform the Community Multiscale Air Quality Modeling System (CMAQ) used for SIP development (Figure 5).[58] CARB also deploys Mobile Research Platforms to further characterize emission sources. The most recent large-scale multi-organization study, the Re-Evaluating the Chemistry of Air Pollution in California (RECAP-CA) campaign, occurred in 2021. This two-month campaign integrated aircraft, mobile platforms, remote sensing technologies, and stationary air monitoring sites.[59] The findings help evaluate and refine the accuracy of air quality models like CMAQ and the *California Emissions Projection Analysis Model (CEPAM)*.

Similar efforts, including the *2019 Fire Influence on Regional to Global Environments – Air Quality (FIREX-AQ)* campaign, have informed models like the *First-Order Fire Effects Model (FOFEM)*, which estimates wildfire emissions and assesses the impact of wildfire smoke on regional air quality. CARB has also supported updates to the chemical mechanisms in CMAQ, improving its ability to predict ozone and PM2.5. Studies such as *CABOTS* have evaluated baseline ozone entering California from offshore, highlighting the need for more accurate modeling of global and vertical transport.[60] These comprehensive measurement systems and campaigns strengthen CMAQ's performance and support the development of more effective air pollution mitigation strategies.

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[58] *CMAQ: The Community Multiscale Air Quality Modeling System | US EPA*.

[59] *2022 RECAP-CA and SUNVEx Workshop (noaa.gov)*.

[60] *Faloona, Ian C., et al. "The California baseline ozone transport study (CABOTS)." Bulletin of the American Meteorological Society 101.4 (2020): E427-E445.*

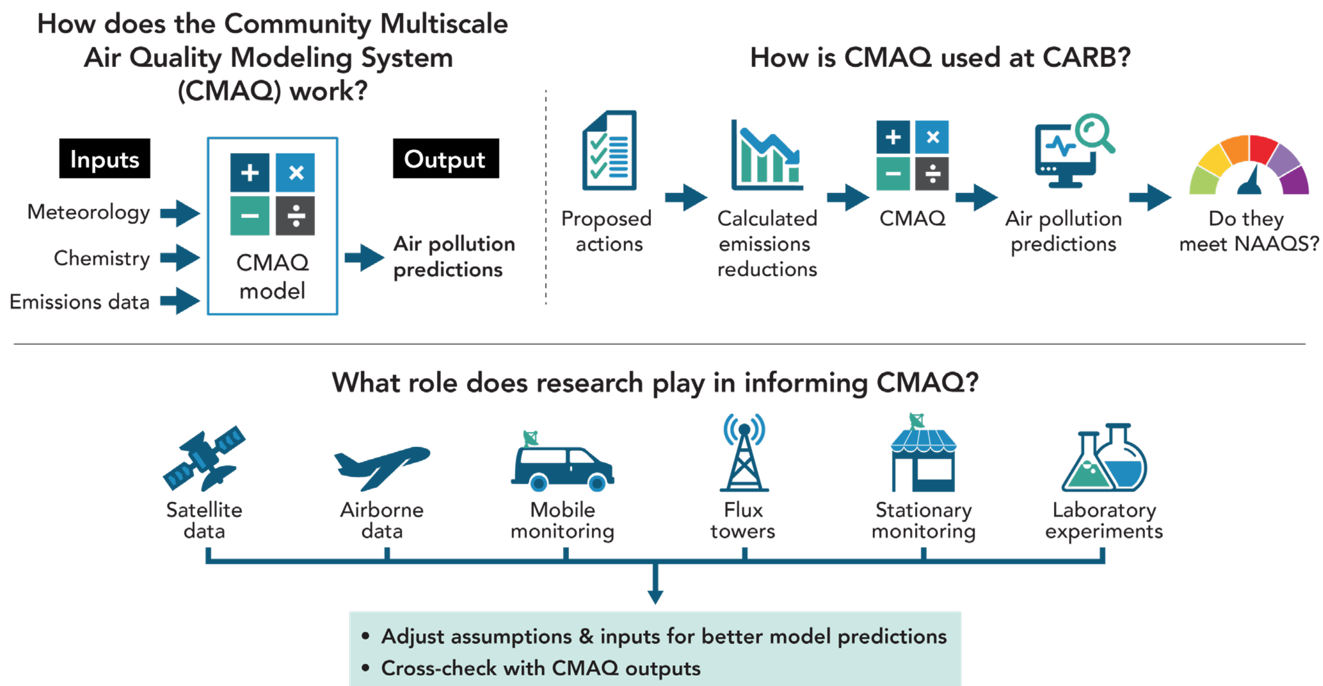

Figure 5: CARB leverages the CMAQ model to create air pollution predictions based on proposed regulatory measures. Research plays an important role in evaluating CMAQ results and in updating and adjusting model assumptions and inputs.

Localized Air Quality Issues and Other Emerging Topics

CARB's ambient air quality research includes initiatives to enhance localized air monitoring and identify sources of air pollution using Mobile Research Platforms. These platforms are equipped with advanced instruments like a Proton-Transfer-Reaction Mass Spectrometer (PTR-MS), capable of detecting air toxics in near real-time, and can move to fill the spatial data gaps between fixed-site monitors, identify pollution hotspots or improvements, and characterize emission sources. Deployment of these resources in areas such as San Ysidro and Avenal, California, in response to community concerns, supports collaborative efforts between local agencies and community organizations.

Research Highlight: Particulate Matter in San Joaquin Valley Air

A CARB-funded project collected hourly air samples for two years to examine the causes of high **PM2.5 levels** in the San Joaquin Valley.

What was found?

- PM2.5 composition varied greatly throughout the day.
- PM2.5 production continues to be influenced by atmospheric chemistry that occurs at nighttime as well as daytime.
- As inorganic PM2.5 has been reduced, organic aerosols, both directly emitted and formed in the atmosphere, are becoming a larger and more important fraction of the total PM2.5 in the San Joaquin Valley.

Why is this work important?

- This project produced hourly PM2.5 measurements, which are over 100x more detailed than **regulatory monitoring data**. Imagine having a photo that is 100x clearer than the original. It can be studied in greater detail and lead to the discovery of previously unknown information.

How will results be used?

To inform and refine air quality improvement strategies that reduce PM2.5 pollution and health impacts in the San Joaquin Valley.

B. Understanding the Drivers of Future Ambient Fine Particulate Matter Formation

Past Research

Previous studies[61] have shown that PM2.5 in the SJV is primarily composed of organic aerosols and ammonium nitrate, with significant contributions from anthropogenic sources, such as vehicles, residential wood burning, food cooking, and agricultural activities. In recent years, the increasing severity of wildfires across California has further elevated ambient PM2.5 levels, leading to more frequent episodes of severe air pollution.[62] The diversity of sources and complexity of the atmospheric processes in the SJV make air pollution control challenging. Understanding the key emission sources, chemical reaction pathways, and atmospheric dynamics is important for developing effective strategies to reduce PM2.5 concentrations in the region.

Current Research

To improve the understanding of PM2.5 sources and chemical reaction pathways, an ongoing study[63] is collecting long-term data on PM2.5 chemical species in the SJV. This study aims to (1) quantify contributions of key primary emission sources (e.g., mobile, biomass burning, cooking, and agricultural activities); and (2) examine how secondary formation pathways and nocturnal residual-layer chemistry influence the concentration and temporal patterns of critical secondary inorganic and organic PM species.[64] This research can provide important insights to inform more effective air pollution control strategies in the region.

Future Research Needs

Timely Drivers

Research finds that health impacts occur at PM2.5 concentrations below the level of the NAAQS, necessitating continued progress on reducing emissions.[65,66] As PM2.5 concentrations decline to meet lower thresholds, maintaining the accuracy and precision of

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[61] CARB Contract 17RD008.

[62] CARB Contract *19RD012*.

[63] CARB Contract *22RD038*.

[64] *Sun, Peng, et al. "PM2. 5 composition and sources in the San Joaquin Valley of California: A long-term study using ToF-ACSM with the capture vaporizer." Environmental Pollution 292 (2022): 118254.*

[65] *Integrated Science Assessment (ISA) for Particulate Matter (Final Report, Dec 2019) | Integrated Science Assessments | Environmental Assessment | US EPA*.

[66] *Supplement to the 2019 Integrated Science Assessment for Particulate Matter (Final Report, 2022) | Integrated Science Assessments | Environmental Assessment | US EPA*.

atmospheric chemistry models becomes increasingly challenging. To support model performance under these conditions, additional data collection and research, particularly focused on the formation, composition, and behavior of organic aerosols, will be critical.

Future Research Priorities

Reducing exposure to PM2.5 remains a public health priority. With stricter and more health-protective standards set by the U.S. EPA, further emissions reductions will be expected. Achieving and maintaining attainment will continue to be challenging in areas such as the SJV and the SoCAB, where unique topography and atmospheric conditions may necessitate regionally tailored strategies. Understudied sources of PM2.5 and other air pollutants are beginning to gain more attention. Community feedback has highlighted primary combustion sources, including those contributing to UFP, as significant health risks. Area-wide sources, such as residential wood burning, continue to affect air quality across the state, especially in the SJV, where strong winter inversions trap emissions near the surface. Additionally, emissions from commercial cooking may warrant further evaluation due to their potential localized impacts.

Understanding ozone formation in these areas is also critical. Ground-level ozone chemistry is influenced by whether the atmosphere is in a “VOC-limited,” “transition,” or “NOx-limited” regime. In VOC-limited conditions, reducing NOx emissions without corresponding VOC reductions can inadvertently increase ozone production. As NOx levels decline further, the atmosphere can move into a transitional regime, where ozone formation may peak before declining into the NOx-limited regime, where additional NOx reductions lead to a decrease in ozone. Many areas struggle to reduce ozone levels despite declining emissions, though greater progress is expected as those regions shift from VOC-limited to NOx-limited chemical regimes over the next 5 to 10 years as NOx emissions are further reduced. Future research is expected to study emission reductions in ozone-sensitive regions.

Below are future research priorities that align with CARB’s research needs and address some of the public’s concerns.

- What chemical compounds and toxic substances are present in wildfire smoke?
- How does smoke composition evolve as it is transported, ages, and interacts with other pollutants?
- How can we enhance our ability to predict smoke dispersion and its impacts to inform more effective prevention and mitigation strategies?

- What measurement techniques and analytical methods can advance our understanding of secondary organic aerosol (SOA) formation, including both gas-phase and aqueous-phase processes?
- What types of field campaigns or long-term monitoring efforts should be prioritized to identify and quantify key SOA precursors and improve our understanding of SOA formation chemistry?
- How can meteorological influences, such as boundary layer dynamics and nighttime residual layer processes, be better characterized to enhance the accuracy of PM2.5 concentration and composition predictions?
- What methodologies should be employed to systematically integrate ground-based observations with upcoming satellite observations to enhance the spatial and temporal resolution of air quality data?

- Which chemical mechanisms require further investigation and inclusion in air quality models to enhance predictive accuracy?
- In which region and under what conditions are we transitioning into NOx-limited regimes, and what implications does this have for current and future air quality management strategies?
- Are there overlooked or underestimated sources of ammonia (NH_3), NOx, or other key precursors that may explain discrepancies between observations and model outputs?
- What additional precursor compounds should be prioritized for further study to improve our understanding of atmospheric chemical interactions?

- Which emerging sources of air pollution may significantly contribute to PM and pose elevated toxicity and exposure risks?
- What additional information is needed to improve CARB's understanding of PM composition, especially in communities impacted by a complex mix of sources?
- What factors are driving the continued rise in average PM2.5 concentrations in certain regions, and to what extent can this be attributed to the prevailing chemical regime (e.g., atmospheric oxidation potential) versus primary emission sources?

C. Understanding the Challenges of Meeting National Ambient Air Quality Standards in a Changing Climate

Past Research

In California, climate change is intensifying a range of serious challenges, including wildfires, coastal erosion, water supply disruption, threats to agriculture, the spread of insect-borne diseases, and ongoing health risks from air pollution. Rising temperatures, coupled with continued fossil fuel use, are worsening levels of PM2.5 and ozone. Without reductions in anthropogenic emissions, climate change is projected to degrade ozone air quality statewide, increasing the frequency of air quality standard exceedances.[67] While some less urban areas may see ozone improvements by 2035 if planned emissions reductions are implemented, regions such as the SoCAB and the San Francisco Bay Area are expected to continue experiencing elevated summertime ozone levels.

Current Research

The increasing severity of wildfires is already having a measurable effect on air quality.[68] In 2020, California experienced smoke from over 7,000 wildfires, compounded by record-breaking heat waves. These conditions led to Southern California's worst air pollution and highest number of unhealthy air quality days since the mid-1990s. There were 157 days of high ozone across Los Angeles, Orange, Riverside, and San Bernardino Counties—the most since 1997. More recently, wildfires intensified by prolonged drought have continued to cause significant losses in the Los Angeles region.

Rising temperatures increase emissions of VOCs and GHGs (Figure 6). Higher temperatures accelerate biogenic emissions from trees and other vegetation, as well as the rate of ozone formation, especially in urban areas where natural and anthropogenic emissions interact. In 2021, CARB and NOAA led the RECAP-CA study to evaluate ozone and PM2.5 chemistry in the SoCAB. This series of work highlighted the complexity of managing air pollution in densely populated regions with mixed emission sources, even to this day.[69, 70]

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[67] *Zhu, Shupeng, Jeremy R Horne, Michael Mac Kinnon, G S Samuelsen, and Donald Dabdub. 2019. "Comprehensively Assessing the Drivers of Future Air Quality in California." Environment International 125: 386–98.*

[68] *McClure, Crystal D., and Daniel A. Jaffe. "US particulate matter air quality improves except in wildfire-prone areas." Proceedings of the National Academy of Sciences 115.31 (2018): 7901-7906.*

[69] *Pfannerstill, Eva Y., et al. "Temperature-dependent emissions dominate aerosol and ozone formation in Los Angeles." Science 384.6702 (2024): 1324-1329.*

[70] CARB Contracts 20RD002, 20RD003, and 20AQP012.

As emissions and climate variables shift simultaneously, accurately predicting future changes remains challenging. Continued improvements to emission inventories and the expansion of observational datasets are essential for deepening our understanding and effectively responding to these dynamic atmospheric conditions.

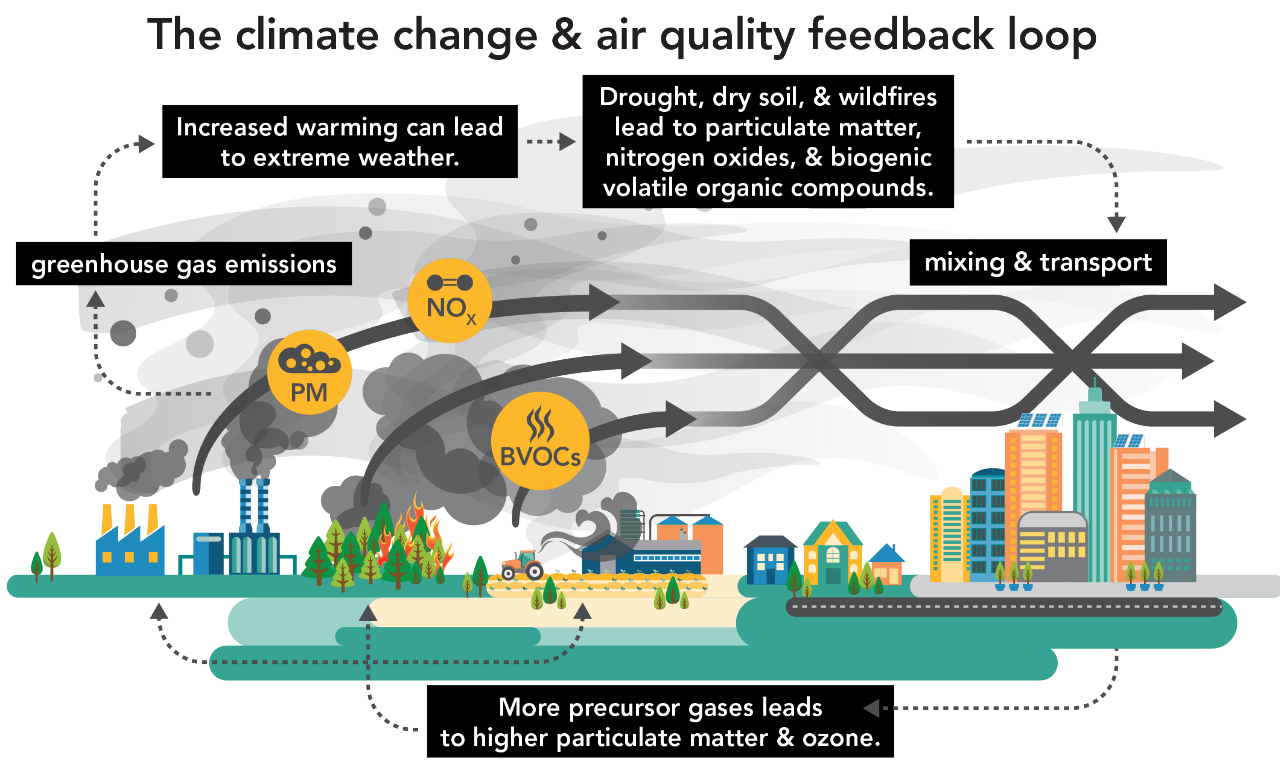

Figure 6: How does climate change impact air pollution?[71, 72]

Future Research Needs

Timely Drivers

Despite the growing air quality challenges posed by climate change, California must still meet the health-protective NAAQS. This includes the 2008 8-hour ozone standard of 75 ppb by 2031 and the 2024 annual PM2.5 standard of 9 μg/m³ by 2032. Developing effective SIPs requires robust data to improve regional air quality models and guide optimal emission reduction strategies. It is especially important for regions with persistent attainment

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[71] *Jaffe, Daniel A., et al. "Scientific assessment of background ozone over the US: Implications for air quality management." Elem Sci Anth 6 (2018): 56.*

[72] *Fu, Tzung-May, and Heng Tian. "Climate change penalty to ozone air quality: review of current understandings and knowledge gaps." Current Pollution Reports 5 (2019): 159-171.*

challenges, like the California-Mexico border area, the SJV, and the SoCAB. As climate change alters atmospheric dynamics, more comprehensive data is also needed to improve model accuracy and better reflect evolving pollution patterns.

Future Research Priorities

Current climate scenario modeling is typically performed at very large geographic scales. More work is needed to integrate future climate scenarios into California-specific air quality models. With increasingly stringent NAAQS, reducing uncertainty around climate impacts on air quality is essential for evaluating various mitigation strategies.

Many regions in California are already experiencing climate change impacts. Areas like the Salton Sea, Mono Lake, South Owens Valley, Mojave and Sonoran Deserts, and the SJV experience frequent dust storms. Dust poses serious health risks in the Salton Sea region, while residents of the SJV are concerned about valley fever linked to dust exposure.

Wildfire smoke continues to raise concerns, both during active fires and afterward. These events result in short-term spikes in air pollution and potential longer-term health effects from lingering dust and ash.

- How can we deepen our understanding of the interactions between air quality, meteorology, and climate in the context of evolving air quality and climate policies?
- What is the role of additional observational data and higher-resolution models in capturing these dynamics?
- Which regional factors most significantly influence air quality under changing climate conditions?
- What climate change scenarios should be integrated into California's air quality models to ensure robust planning?
- Do climate penalties differ between NOx-limited and VOC-limited regions, and how might these differences affect pollution control strategies?
- How will climate penalties and extreme weather events affect California's ability to achieve and maintain air quality attainment goals?

- What are the most effective emission reduction strategies to address air quality disparities, and how durable are these reductions over time?
- How does climate change influence air quality disparities, particularly regarding heat, PM2.5, and ozone?

- How will natural and working lands (NWL) influence air quality in California under changing climate conditions?
- How are the nitrogen and carbon cycles expected to evolve across the state under various climate scenarios, and what implications will these changes have on emissions?

- What are the co-benefits of air quality and climate strategies?
- What research is needed to support future Scoping Plan development in quantifying the economic, air quality, health, equity, and climate co-benefits of various proposed strategies?
- What are the economic, health, and environmental costs of inaction in addressing air quality and climate change simultaneously?

- How will climate change affect the future severity and frequency of wildfires?
- What impact will these changing wildfire patterns have on air quality?
- How does the expansion of urban sprawl into the wildland-urban interface (WUI) influence the risk of structure fires under future climate scenarios?

D. Air Quality Impacts of Ambient Volatile Organic Compounds

Past Research

VOCs are organic compounds that evaporate readily at room temperature. They are emitted from a variety of sources, including industrial activities, motor vehicles, household products, and natural vegetation. VOCs contribute to the formation of secondary pollutants such as ozone and PM, and some are associated with adverse health effects due to their toxicity.

Developing effective VOC control strategies in California is complex due to the state's varying atmospheric chemical regimes. Field campaigns like the *California Research at the Nexus of Air Quality and Climate Change (CalNex)*[73,74] and *Deriving Information on Surface Conditions*

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[73] *Ryerson, TBea, et al. "The 2010 California research at the Nexus of air quality and climate change (CalNex) field study." Journal of Geophysical Research: Atmospheres 118.11 (2013): 5830-5866.*

[74] CARB Contract *08-316*.

from COlumn and VERtically Resolved Observations Relevant to Air Quality (DISCOVER-AQ) identified motor vehicles and petroleum operations as major VOC sources in the SoCAB and the SJV.[75] VOC and carbon monoxide (CO) enhancement ratios[76,77] from CalNex, showed that VOC emissions from gasoline vehicles in Los Angeles have reduced by nearly two orders of magnitude since 1960. However, ethanol, a VOC used as a biofuel amendment to gasoline, remained a key VOC in urban Los Angeles.[78] Petroleum operations were also identified as the major source for several VOC species. Because VOC reactivity depends on factors such as temperature and location, region-specific strategies may be important to consider, particularly across Northern, Central, and Southern SJV. However, the observed shifts towards the NOx-limited regime in many parts of the state may signify that reducing NOx may be more effective than targeting VOCs alone. These and other research findings highlight the importance of simultaneously evaluating NOx and VOC emissions to identify additional opportunities for air quality improvement in the state.[79, 80, 81]

Current Research

CARB recently installed a high-sensitivity mass spectrometer at the Fresno-Garland Supersite to carry out continuous on-site measurements of speciated VOCs. The Supersite is now a *Photochemical Assessment Monitoring Station (PAMS)* supporting a comprehensive ozone precursor monitoring program. To further enhance VOC monitoring capabilities, CARB is evaluating additional advanced measurement technologies for potential integration. Beyond stationary monitoring, CARB is expected to deploy VOC instruments in its Mobile Research Platforms to support several field studies over the next five years. These efforts will help identify emission hotspots and quantify contributions from key point sources across California.

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[75] *Young, Dominique E., et al. "Influences of emission sources and meteorology on aerosol chemistry in a polluted urban environment: results from DISCOVER-AQ California." Atmospheric Chemistry and Physics 16.8 (2016): 5427-5451.*

[76] *Barletta, Barbara, et al. "Emission estimates of HCFCs and HFCs in California from the 2010 CalNex study." Journal of Geophysical Research: Atmospheres 118.4 (2013): 2019-2030.*

[77] *Warneke, Carsten, et al. "Multiyear trends in volatile organic compounds in Los Angeles, California: Five decades of decreasing emissions." Journal of Geophysical Research: Atmospheres 117.D21 (2012).*

[78] *De Gouw, J. A., et al. "Increasing atmospheric burden of ethanol in the United States." Geophysical Research Letters 39.15 (2012).*

[79] *McDonald, Brian C., et al. "Volatile chemical products emerging as largest petrochemical source of urban organic emissions." Science 359.6377 (2018): 760-764.*

[80] *Wu, Shenglun, et al. "O3 Sensitivity to NO x and VOC During RECAP-CA: Implication for Emissions Control Strategies." ACS ES&T Air 1.6 (2024): 536-546.*

[81] *Stockwell, Chelsea E., et al. "Urban ozone formation and sensitivities to volatile chemical products, cooking emissions, and NO x across the Los Angeles Basin." EGUsphere 2024 (2024): 1-24.*

Figure 7: Large cities and urban centers can have a complex mixture of VOC emissions. Los Angeles is an example of a city with a mixture of anthropogenic and biogenic VOCs. Los Angeles air basin is currently transitioning from VOC-limited to NOx-limited regime. Continued reductions in VOC emissions will be important for lowering ozone levels during this transitional period. More work is needed to understand which reductions will lead to overall reductions in ozone.

Future Research Needs

Timely Drivers

Awareness is growing about the impact of anthropogenic VOCs emitted from consumer products, combustion, and industrial processes on air quality and health. Understanding the role of VOCs in forming secondary air pollution, especially in non-attainment areas, is important for PM2.5 and ozone NAAQS attainment and future SIP development. In particular, additional research on oxygenated VOCs (OVOC), such as formaldehyde and ethanol, may further help assess the importance of their roles in especially as the climate warms. As the *CAPP* continues efforts to reduce toxic exposures in overburdened communities, VOCs are likely to play an increasingly important role in identifying and mitigating localized pollution sources.

Future Research Priorities

As more zero-emission vehicles (ZEVs) are adopted and conventional vehicles are phased out, VOC sources and their atmospheric concentrations will shift. To support regional air quality models, additional air monitoring and data analysis studies to track changes in atmospheric chemistry regimes are a priority.

- How does a NOx-limited environment influence PM2.5 composition and secondary aerosol formation?
- How are VOC emissions evolving in densely populated areas like the SoCAB, and what are the implications for SOA formation?
- What roles do consumer products, cooking, and other non-mobile sources play in VOC emissions and regional air quality?
- Are there localized air quality impacts from shifts in atmospheric chemistry?

- What role do oxygenated VOCs from dairies and other agricultural activities play in the SJV's air quality?
- How do these OVOCs and NH_3 react with other precursors to influence the formation of secondary pollutants?

- As the climate changes, how will biogenic VOC (BVOC) emissions from trees change, and what are the implications for air quality?
- How can we inform heat mitigation strategies, such as urban tree planting, by selecting species with lower BVOC emissions?
- What improvements are needed in biogenic emissions inventories to enhance air quality model performance?

- What monitoring methods, modeling tools, or community engagement strategies can improve the quantification of toxic VOC exposure risks in communities adjacent to industrial operations?

E. Air Quality Impacts from Dairy and Agricultural Operations

Dairy farms emit both NH_3 and VOCs, which contribute to the formation of PM2.5 and ozone. While mitigation strategies have traditionally focused on reducing NOx emissions, a deeper understanding of dairy-related VOC emissions is increasingly important, especially in non-attainment areas like the SJV. Emissions from cattle housing, manure lagoons, and silage-based feed storage may significantly influence regional air quality.[82]

In parallel, CARB has investigated soil NOx emissions using ambient monitoring and satellite remote sensing, leading to the additional utilization of a California-calibrated DeNitrification-DeComposition (DNDC) biogeochemical model. Although initial findings suggested soils contribute minimally to the state's NOx inventory, more recent research indicates that agricultural soils may play a larger role than previously estimated. Continued investigation is important, as many agricultural regions in California remain out of attainment for ozone and PM2.5 NAAQS.

Past Research

To improve activity data for the dairy and livestock sector, CARB worked with the Regional Water Quality Control Boards (RWQCB) and other agencies to develop the *California Dairy and Livestock Database (CADD)*,[83] which contains the state's most comprehensive facility-level animal population data. CADD is now publicly available. Additionally, the California Dairy Emissions Model (CADEM) was developed to estimate facility-level emissions of NH_3 and GHGs such as methane (CH_4), carbon dioxide (CO_2), and nitrous oxide(N_2O) from dairies under different management practices. Refer to the *Climate Research* chapter for more information on CADD and CADEM.

Current Research

Validating and refining CADEM is a key focus of CARB's dairy research. One ongoing contract[84] analyzes lagoon and settling basin wastewater to determine typical carbon and nitrogen inputs for California dairies, which will inform CADEM. This effort complements in-house efforts to measure dairy GHG emissions, which are being compared against long-term data to evaluate model performance. Another contract[85] is developing a user-friendly, web-based tool version of CADEM to support broader applications. Integration of facility-level data from CADD will further enhance CADEM's accuracy. Once complete, CADEM can serve

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[82] *Hafner, Sasha D., et al. "Emission of volatile organic compounds from silage: Compounds, sources, and implications." Atmospheric Environment 77 (2013): 827-839.*

[83] *California Dairy & Livestock Database (CADD) | California Air Resources Board*.

[84] CARB Contract 22RD013.

[85] CARB Contract 23RD031.

as a practical tool for CARB and dairy producers to better understand facility-level GHG mitigation decisions.

Separately, CARB is working with a Subject Matter Expert Review Panel (SMERP)[86] to evaluate the current understanding of soil NOx emissions and assess the current inventory values. Following the review, CARB will collaborate with other researchers to address data gaps and improve monitoring.

Future Research Needs

Timely Policy Drivers

Senate Bill (SB) 1383 (Lara, Stats. of 2016, Ch. 395) set a goal to reduce statewide methane emissions, including from dairy and livestock, by 40% below 2013 levels by 2030. Strategies to reduce methane may also reduce co-pollutants like PM and VOCs. A 2022 analysis identified technology interventions that could also lower PM and NOx emissions. Since the legislation mandates tracking of CH_4 emissions reductions, there is an opportunity to also track the trends of co-pollutants and quantify associated air quality benefits, if any. Given the significant contributions of the dairy and agricultural sector to emissions in the SJV, this remains an important area of research to support future SIP targets.

Future Research Priorities

Agricultural practices, such as burning, tilling, fertilizing, and harvesting, can affect air quality, especially in nearby communities. Residents have raised concerns about new crop and pesticide use. Ongoing research on agricultural soil NOx emissions will consider recommendations from the SMERP, which are particularly relevant in regions like the SJV, where multiple agricultural NOx sources, including off-road equipment, contribute to overall emissions. Differentiating NOx emissions among these sources remains a key challenge, highlighting the need for improved monitoring methods or analysis techniques. Future studies can also evaluate the air quality impacts of climate-smart practices, such as the use of organic fertilizers or carbon-sequestering farming methods.

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[86] CARB Contract 23RD017.

- What disproportionate air quality impacts do rural communities experience from agricultural activities, including pesticide application and dairy operations?
- How do fallow fields affect air quality in nearby communities, particularly in terms of dust and particulate matter?
- What strategies can be implemented to reduce these disparities and improve air quality outcomes for rural populations?

- How do various farming practices, such as fertilizer application and irrigation, influence soil NOx emissions?
- How are these emissions expected to change with the adoption of climate-smart agricultural strategies?
- In what ways will climate change affect soil emissions and the potential for carbon sequestration in agricultural lands?

- What specific dairy, silage, and digestor activities warrant further investigation?
- How can research on these activities improve our understanding and quantification of emission factors for NH_3, NOx, total organic gases, N_2O, toxic pollutants, and CH_4?

- What emissions reductions can be achieved through control technologies applied to dairy digesters and alternative manure management?
- What additional real-world NH_3 measurements are needed to validate and optimize promising emission reduction strategies for PM2.5?

F. Reducing Air Quality Disparities

Low-income and communities of color continue to experience health and opportunity gaps resulting from discriminatory land-use practices. AB 617 and similar programs help to center solutions for closing those gaps around community needs through robust community engagement. AB 617 data shows that community-led solutions are cutting emissions, strengthening enforcement of clean air policies, and delivering cleaner, healthier air around the state.[87]

Past Research

Much of the ambient air quality research has been sector- or pollutant-based, targeting specific emission sources like vehicles or industrial operations. These targeted studies have effectively addressed air pollution challenges caused by major sources, benefiting communities near major roadways or industrial areas, which are often located near overburdened and low-income neighborhoods. While these efforts did not directly address the disparity between low- and high-income areas, the results of these studies have allowed researchers to study the air quality of vulnerable populations (i.e., elderly and children) and Californians living in the overburdened neighborhoods or disadvantaged communities (DACs). This research, which was designed to aid SIP development, has partly addressed the disparity gap by informing regulators and policymakers about near-roadway air pollution exposure, air pollution dispersion, localized atmospheric chemistry, and source-level activities that affect exposure risks. There are additional efforts being conducted by the regional government to further understand the exposure to air pollution.[88]

Current Research

CARB's current research supports efforts to reduce air quality disparities across California, with a focus on understanding pollutant sources and their impacts on overburdened communities. One project is examining long-term trends in PM2.5 chemical composition in the SJV to improve understanding of SOA formation and evolving PM2.5 sources. Another study[89] investigates the growing air quality impacts of wildfire, emphasizing the importance of proactive measures to protect the vulnerable population.

CARB is also conducting a major multi-site field study to improve understanding of secondary pollutant formation and the role of precursor emissions in driving PM2.5.[90] To further address community concerns, CARB is expanding research on air toxics, particularly in areas near specialized industries. In response to concerns about metal emissions, CARB funded the development of a user-friendly, portable, real-time metals analysis instrument (TARTA).[91] This tool has the potential to significantly improve the measurement of airborne toxic metals in communities.

[87] *OCAP_APR2024_Final.pdf*.
[88] *MATES V*.
[89] CARB Contract *23RD006*.
[90] CARB Contract *21RD010*.
[91] CARB Contract *17RD022*.

Future Research Needs

Timely Drivers

CAPP will remain a key policy driver for future research. As the program evolves, new community-specific issues will emerge that warrant further investigation. Upcoming goals to reduce exposure to air toxics will guide research efforts focused on targeted monitoring, the development of new measurement tools, and improved methods for communicating findings to the public.

Future Research Priorities

- Which sources and pollutants of concern (e.g., EtO, PCBTF, PFAS, VOCs, and Metals) should be further investigated to improve our understanding of their spatial distribution across California?
- Are these pollutants persistent concerns in AB 617 and other overburdened communities, and what additional data or research is needed to inform effective mitigation strategies?

- Do the impacts of climate change, such as extreme heat, PM2.5, and ozone, increase health and environmental burdens in overburdened communities?
- What strategies are most effective for achieving and sustaining long-term air quality improvements in these communities?

- What are the most effective strategies for developing, funding, and implementing equitable and actionable community air monitoring programs?
- How can transparency be improved in air monitoring siting decisions, and what best practices support effective deployment of fence-line monitoring in impacted communities?
- How can CARB further support the development of community-based air monitoring networks that prioritize data sharing, quality, storage, and other key practices?
- In what ways can satellite data be leveraged, and which areas would benefit from enhanced tools, modeling, and monitoring technologies, including satellites and other advanced systems?

- Which research findings can inform existing or new air quality mitigation strategies?
- Which strategies are most effective in reducing disparities for communities near roadways, in rural areas affected by agricultural emissions, or in WUI?
- What additional research can help protect communities located near industrial operations and other stationary sources from harmful air pollution?

- Which newly identified non-attainment areas require additional data on PM2.5 and its precursors, and which communities are most likely affected?
- What enhancements to modeling and forecasting tools are needed to better inform air quality improvement strategies, particularly in overburdened communities?
- How durable are current emission reductions, and how can research more effectively support CAPP in reducing community-level pollution?

Chapter 3: Climate Research

A. Introduction

The *Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6)* warns that without significant global action, warming will exceed 1.5°C by the 2030s. A 2°C increase would further heighten risks to human health, livelihoods, and biodiversity. California is particularly vulnerable, already experiencing severe environmental impacts from rising temperatures, prolonged droughts, declining snowpacks, and more frequent and intense wildfires.

California has developed a robust climate policy portfolio through landmark legislative and regulatory actions. California's *2022 Scoping Plan Update* provides a sector-by-sector roadmap that outlines a technologically feasible and cost-effective path to achieving the State's climate targets (Figure 8). This comprehensive approach helps reduce greenhouse gas emissions (GHG), promotes energy resiliency, improves public health, supports disadvantaged and low-income communities, and fosters economic growth and job creation.

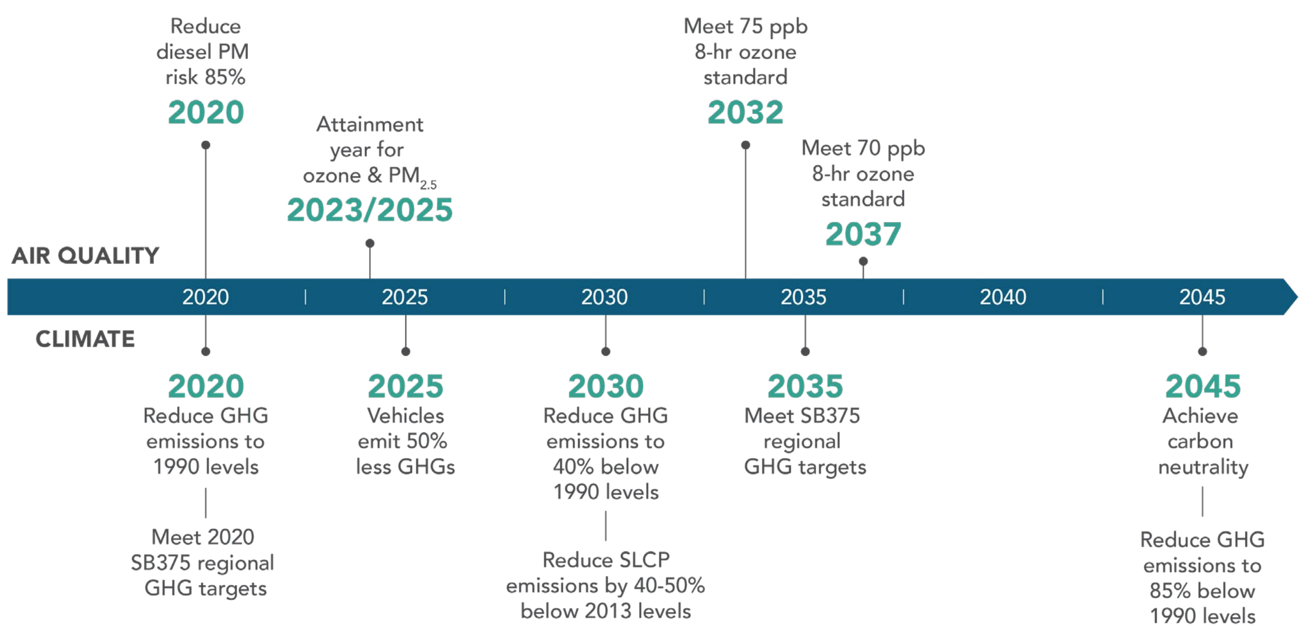

Figure 8: California climate change mitigation goals.

How is Climate Research Used at the California Air Resources Board?

CARB's Research Program supports both external and in-house research initiatives to track and characterize GHG emissions, assess co-benefits to health, the environment, and the economy, and explore strategies to reduce emissions of carbon dioxide (CO_2), nitrous oxide (N_2O), and Short-Lived Climate Pollutants (SLCP) like black carbon (BC), methane (CH_4), and hydrofluorocarbons (HFCs). The *Healthy Soils Program* and the *Dairy Digester Research and Development Program* are a few of the key programs that inform these research initiatives.

The Research Program also examines the interactions between air quality and climate to better anticipate California's future environmental conditions (see the *Ambient Air Quality Research* chapter for more on understanding the challenges in meeting National Ambient Air Quality Standards (NAAQS) in a changing climate).

Emerging technologies, such as satellites, drones, low-cost sensors, mobile platforms, and ground-based remote sensing, are increasingly used to collect high-resolution data on GHG emissions and related activities, helping inform effective emission reduction strategies.

B. Greenhouse Gas Emissions and Sinks from Natural and Working Lands

Past Research

California has over 40 million hectares of natural and working lands (NWL), including croplands, grassland, shrubland, forest, and developed lands. These lands can act as either sources or sinks of GHG. CARB's previous research focused on N_2O emissions from fertilized agricultural lands[92] using field monitoring and biogeochemical modeling across major California cropping systems. In collaboration with state agencies, CARB assessed key cropping systems, agricultural regions, and nitrogen sources. These projects established baseline N_2O emissions and identified the environmental and management factors that influence them. These efforts, spanning both in-house and collaborative projects, resulted in a more accurate N_2O emissions inventory,[93] supported California's first NWL carbon stock inventory,[94] and provided scientific support for climate-smart practices under the Healthy Soils Program.[95]

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[92] *Nitrous Oxide (N2O) Emissions from California Lands | California Air Resources Board*.*https://ww2.arb.ca.gov/our-work/programs/soil-emissions-california-lands/nitrous-oxide-n2o-emissions-california-lands*.

[93] *Current California GHG Emission Inventory Data | California Air Resources Board*.

[94] *Technical Support Document for the Natural & Working Lands Inventory*.

[95] *CDFA Healthy Soils GGRF Quantification Methodology*.

Current Research

CARB's in-house NWL research has focused on soil organic carbon (SOC), which is important for storing carbon in agricultural lands. Increasing SOC storage is a key strategy for achieving carbon neutrality. This work also factors in climate change projections, like higher CO_2 levels, rising temperatures, and shifting rainfall patterns. Research on ways to enhance soil carbon sequestration and promote sustainable soil management can help to identify practices that cut GHG emissions and improve air quality, particularly in agricultural regions like the San Joaquin Valley (SJV).

In response to public concerns, CARB recently initiated a project[96] to examine how pesticides, especially fumigants, may increase N_2O emissions from soils. Early studies suggest that fumigants can raise emissions under certain scenarios. This project will measure N_2O emissions in California's agricultural fields over time and run laboratory experiments to clarify how pesticides and environmental factors influence emissions, helping to refine the state's N_2O inventory.

Future Research Needs

Timely Drivers

AB 1757 (Garcia, Stats. of 2022, Ch. 341) requires CARB to develop standardized methods for tracking GHG emissions, reductions, carbon sequestration, and other benefits from NWL. In collaboration with other agencies, CARB must also set targets for natural carbon sequestration and nature-based climate solutions for 2030, 2038, and 2045.[97] These solutions include beneficial fire use, fuel load reduction, conserving or restoring forests, chaparral, shrublands, and grasslands, healthy soil practices, and urban greening projects. AB 1757 is expected to be a significant driver for future research priorities over the next five years.

Future Research Priorities

- What additional information can satellite data provide to support carbon sequestration monitoring and verification in California's NWL?
- What types of land-based measurements, such as flux tower data, field plot inventories, and soil sampling, are needed to enhance carbon mapping efforts and improve estimates of carbon sequestration and key GHG emissions?

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[96] CARB Contract *22RD036*.

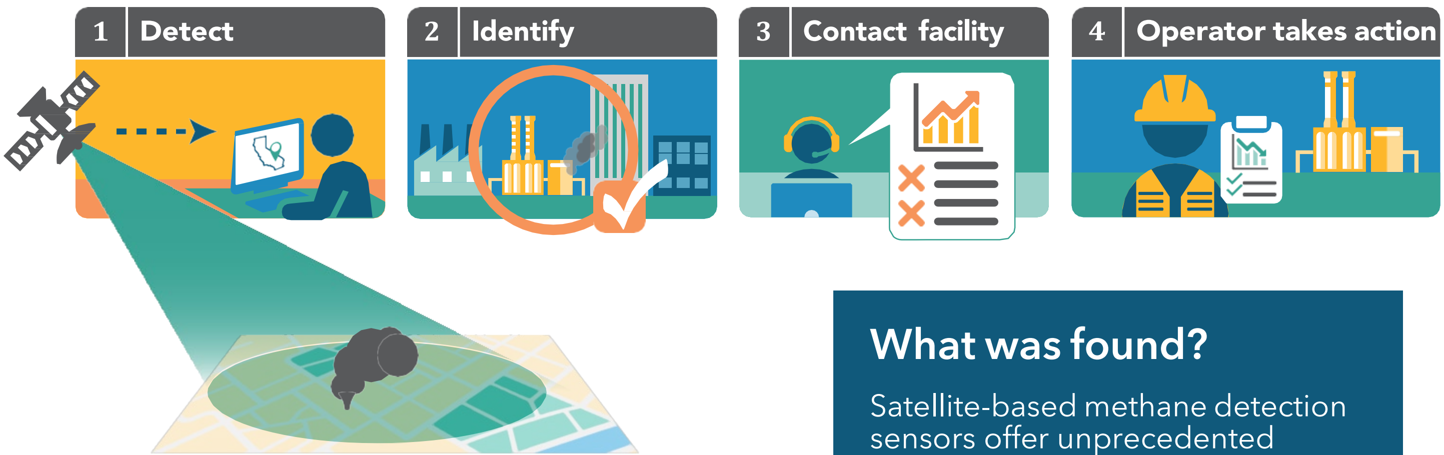
[97] *California's Nature-Based Solutions Climate Targets*.

- What research is needed to deepen understanding of carbon stocks, fluxes, and dynamics across California's diverse NWL landscapes to inform NWL inventories?
- How can estimates of biomass utilization, feedstocks, and wildfire fuel loading in different biomes support remission reduction and land management programs?
- In what ways can carbon flux data be better integrated to inform and refine NWL inventories?

- What research gaps need to be addressed to improve modeling accuracy and better predict outcomes for strategic forest management scenarios?

- How does transitioning from conventional to organic agriculture impact carbon stocks and GHG fluxes?
- How can California's Nature-Based Solutions Climate Targets be better integrated, quantified, and monitored with greater accuracy?
- What methods can be used to quantify the co-benefits, costs, and economic value of these nature-based actions?

Research Highlight: Monitoring Methane with Satellites



Methane is a short-lived climate pollutant and a powerful greenhouse gas. Satellites can record images of methane leaks, which appear as plumes trailing away from the source of emissions.

All methane plume data acquired by CARB will be made publicly available. CARB will continue to work with communities and other agencies to ensure these data broadly support the needs of Californians.

What was found?

Satellite-based methane detection sensors offer unprecedented opportunity to detect large, concentrated methane sources over California.

Why is this work important?

- It identifies large methane leaks.
- Allows CARB to work with agencies and industry to reduce greenhouse gases and protect the environment.

How can satellite data be used?

With the amendment of CARB's Oil & Gas Regulation, CARB can require actions to fix identified methane leaks.

Other methane sectors could consider similar actions.

C. Measurement Systems on Local and Statewide Scales

CH_4 is an SLCP with a global warming potential (GWP) approximately 25 times greater than CO_2 over a 100-year period. However, because CH_4 remains in the atmosphere for about a decade, reducing its emissions can more rapidly slow the pace of global warming. Advances in analytical techniques have improved CH_4 measurement capabilities, but limitations persist, such as reliance on data from individual landfills or infrequent sampling that fails to capture daily or annual emission totals. Additionally, many estimates depend on assumptions that introduce uncertainties. Addressing these gaps can improve the accuracy of source-specific CH_4 emissions estimates and track change over time.

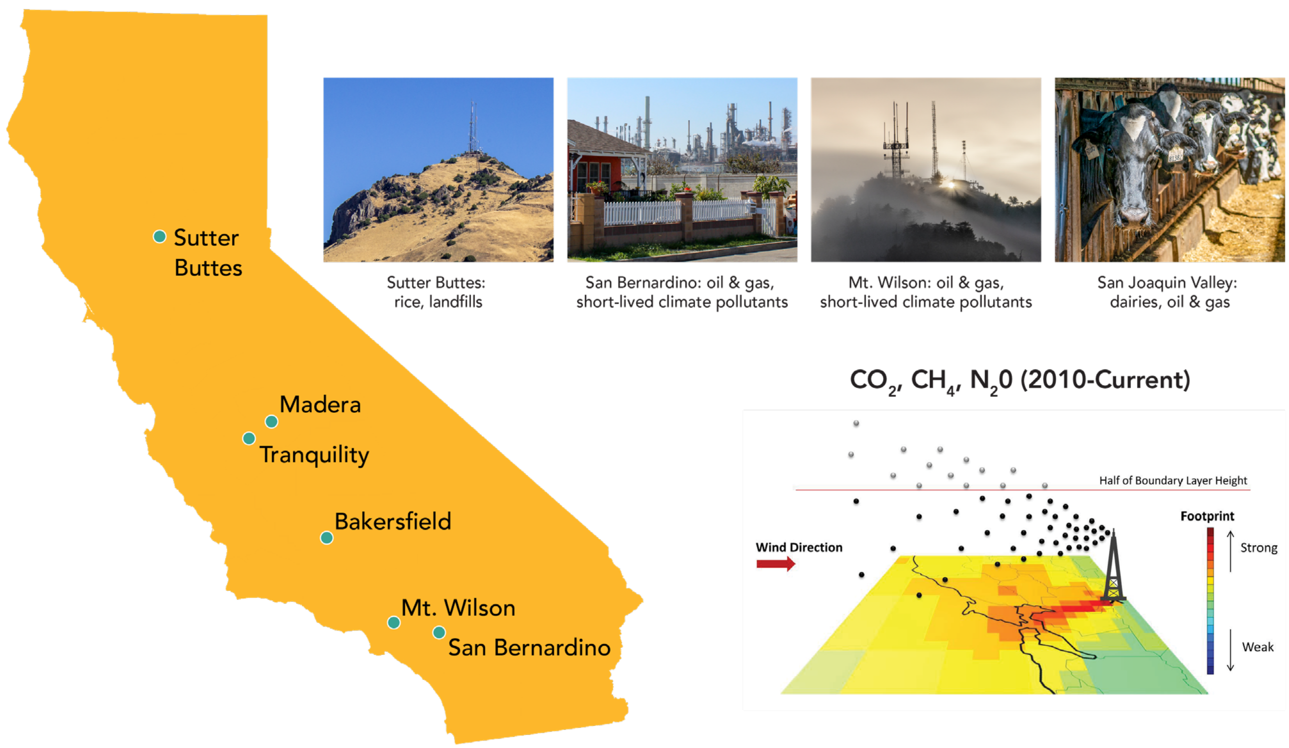


Figure 9: The left panel shows the locations of CARB's statewide GHG network monitors. The upper right panel shows photographs of various monitoring stations, and the bottom right panel shows a heat map of GHG concentrations.

Past Research

Statewide Studies

CARB conducted in-house research and used external research contracts to estimate statewide and regional CH_4 emissions through inverse modeling. This method combines CH_4

measurements from aircraft and tower networks with meteorological models (see Figure 9).[98, 99] While this approach provides a broad overview of emissions, its precision decreases at finer scales, limiting its ability to identify individual emission sources.

In partnership with the California Energy Commission (CEC), CARB has supported airborne studies that use state-of-the-art remote sensing technology known as CH_4 plume imagers to detect large and concentrated emission sources, such as leaks from oil and gas facilities or landfills. This tool complements regulatory measures by helping operators locate fugitive emissions that can be investigated and addressed by direct action. These results have prompted the State to support the use of these data[100] through amendments to the *Oil and Gas Methane Regulation*, which includes provisions for methane identified with remote sensing.

Localized Studies

CARB deployed and maintained flux towers for multiple years to estimate CH_4 emissions over a landfill. This work complemented CARB-funded external research projects that used mobile remote sensing[101] and a small aircraft to estimate emissions from many landfills.[102] CARB also used a mobile van to quantify landfills and deployed a ground-based system to survey about 10% of Northern California's active natural gas wells. Results[103] showed a “fat-tail” distribution, where a small number of sources account for a large share of emissions, an insight also seen by the statewide airborne surveys of oil and gas wells.[104] These studies highlight that a small number of sources may contribute disproportionately to statewide CH_4 emissions. CARB also supported efforts to monitor around Aliso Canyon after a large methane blowout. A *Summary Report* documents these efforts. Both of these research areas highlight the importance of an observation system, such as satellites, that can frequently scan infrastructure across the state.

Current Research

CARB is expanding CH_4 observations at landfills through in-house research and collaborating with commercial and academic partners. New contracts will test new, low-cost techniques for more frequent CH_4 emissions estimates. CARB also continues to use inverse modeling with

[98] CARB Contracts *15-302*, *09-348*, and *11-306*.

[99] *Cui, Yu Yan, et al. "A multiplatform inversion estimation of statewide and regional methane emissions in California during 2014–2016." Environmental science & technology 53.16 (2019): 9636-9645.*

[100] *Satellite Data Purchase Program | California Air Resources Board*.

[101] CARB Contract *17RD021*.

[102] CARB Contracts *16RD018* and *18RD032*.

[103] *Mobile sampling of methane emissions from natural gas well pads in California - ScienceDirect*.

[104] *Final Report for the California Methane Survey*, *2020 Airborne Methane Survey Report*, CARB Contract 22RD001 *Final Report*, and *Summary Report of the 2020, 2021, and 2023 Airborne Methane Plume Mapping Studies*.

satellite data and its GHG monitoring network to better understand CH_4 emission patterns and meteorological influences.

CARB also aims to expand its use of satellite data to detect local CH_4 sources. The California State Budget Act of 2022 has allocated *$100 million to acquire satellite data for methane plume imaging in California* from a commercial satellite company.

Future Research Needs

Timely Drivers

AB 32 (Nunez, Stats. of 2006, Ch. 488), *SB 32* (Pavley, Stats. of 2016, Ch. 249), and *AB 1279* (Muratsuchi, Stats. of 2022, Ch. 337) will continue to drive future research priorities. CARB will continue the work described above and support California in meeting the climate goals in these landmark statutes.

Future Research Priorities

- How can remote sensing and other innovative technologies support GHG programs?
- Which tools and methods can effectively and accurately measure GHG emissions on a more frequent basis?

D. Dairy Emissions from Changes in Management Practices

CARB reports that the dairy sector accounts for 43% of the State's anthropogenic CH_4 emissions, with 21% from enteric fermentation and 22% from dairy manure management.[105] To meet the *Senate Bill 1383* (Lara, Stats. of 2016, Ch. 395) goal of cutting dairy and livestock CH_4 emissions 40% below 2013 levels by 2030, CARB and partners formed subgroups to address key questions related to dairy manure management and enteric fermentation. Subgroup 3 focused on identifying research needs. The resulting *Dairy Research Prospectus* prioritizes refining emission inventories using CA-specific data, improving activity data for dairies, and refining emission estimation methods.

Past Research

CARB has focused on the research gaps identified by Subgroup 3. In 2019, CARB conducted an extensive study measuring methane emissions at 107 dairies using mobile and airborne platforms, confirming that current emission factors accurately represent dairy methane

[105] https://ww2.arb.ca.gov/sites/default/files/2024-09/nc-ghg_inventory_ipcc_all_00-22.xlsx.

emissions in California.[106] This supported the methodology of the current dairy methane emissions inventory for the state.

To improve activity data for the dairy and livestock sector, CARB worked with the Regional Water Quality Control Boards (RWQCB) and other agencies to develop the California Dairy and Livestock Database (CADD),[107] the state's most comprehensive facility-level animal population database, which is publicly available.

CARB also funded a study[108] on ways to reduce CH_4 emissions from enteric fermentation and lagoons. It was determined that feed additives like 3-nitrooxypropanol (3NOP) and nitrate are currently the most effective options. CARB further supported the development of a testing standard to evaluate the effect of feed additives on enteric CH_4 emissions.

Additionally, the development of the California Dairy Emissions Model (CADEM) was initiated.[109, 110] The model estimates the climate benefits of management practices, such as feed additives, anaerobic digesters, and alternative manure management practices to reduce GHG emissions.

Current Research

Validating and refining CADEM remains a key focus of CARB's dairy research. One project[111] analyzes lagoon and settling basin wastewater samples to determine typical carbon and nitrogen flows for California dairies to be used in CADEM. This work complements in-house research measuring dairy GHG emissions to compare and validate CADEM output against long-term emissions data from a typical California dairy farm. Another project[112] is preparing CADEM for deployment as a user-friendly, web-based tool, supported by facility-level data from CADD.

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[106] *Amini, Seyedmorteza, et al. "Evaluating California dairy methane emission factors using short-term ground-level and airborne measurements." Atmospheric Environment: X 14 (2022): 100171.*

[107] *California Dairy & Livestock Database (CADD) | California Air Resources Board*.

[108] CARB Contract *17RD018*.

[109] CARB Contract *19RD028*.

[110] CARB Contract *21RD019*.

[111] CARB Contract 22RD013.

[112] CARB Contract 23RD031.

Future Research Needs

Timely Policy Drivers

SB 1383 continues to be a main driver for estimating dairy CH_4 emissions and studying reduction strategies. CARB's study[113] on progress in meeting the SB 1383 target recommended advancing feed and manure additives, enteric mitigation strategies, expanding the development of dairy digesters, and addressing market barriers to adopting new methods.

Future Research Priorities

- How can models and additional activities data further refine dairy and livestock methane emission estimates under different feeding or manure management practices?
- How can mobile monitoring or inverse modeling be leveraged to further improve emissions estimates?

E. New Refrigerant Technologies and Recycling of Existing Refrigerants

Hydrofluorocarbons (HFCs) are the fastest-growing GHGs in California and have GWPs hundreds to thousands of times that of CO_2. HFCs are used mainly as refrigerants in cooling and heat pump equipment. HFCs are also used as foam-blowing agents, aerosol propellants, solvents, fire suppressants, and inhalers. The American Innovation and Manufacturing (AIM) Act of 2020,[114] and the Kigali Amendment to the Montreal Protocol[115] are driving a national and global phasedown of HFCs, supported by California regulations like *SB 1206* (Skinner, Stats. of 2022, Ch. 884). These measures have paved the way to transition towards low-GWP and HFC-free alternatives. Recycling and reuse can also help prevent unintended emissions during the transition.

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[113] *Analysis of Progress toward Achieving the 2030 Dairy and Livestock Sector Methane Emissions Target (March 2022)*.

[114] 42 U.S.C. § 7675: American innovation and manufacturing.

[115] The Kigali Amendment (2016): The amendment to the Montreal Protocol agreed by the Twenty-Eighth Meeting of the Parties (Kigali, 10-15 October 2016) | Ozone Secretariat.

Past Research

Previous CARB HFC research focused on identifying the primary sources to develop the nation's first statewide HFC inventory. This inventory has helped quantify emissions, understand key sources, and guide regulations targeting the highest-emitting sectors to make progress toward the HFC emission reduction goals of SB 1383.

Current Research

CARB is funding a study[116] to develop a modeling tool to quantify and compare the total lifecycle emissions of virgin and reclaimed refrigerants across sectors. Given the complexities and range of factors associated with life-cycle refrigerant emissions, the inventory and modeling outputs will be accompanied by a qualitative analytical framework to qualify and inform the use of the tool and its application to policy interventions. The project will cover various refrigerants, including key HFCs, hydrofluoroolefins (HFOs), and other alternatives such as non-fluorinated or natural refrigerants.

Future Research Needs

Timely Drivers

SB 1383 directs CARB to reduce HFC emissions 40% below 2013 levels by 2030, while *SB 1206* phases out the sales of high-GWP bulk HFCs starting in 2025. SB 1206 requires an assessment to transition sectors to ultra-low GWP or no-GWP alternatives by 2035. This work will identify remaining gaps or market barriers that may need further research and shed light on further regulatory or legislative measures. As California decarbonizes buildings and shifts to clean-electric technologies, like heat pumps, which often use mid-to-high-GWP HFC, ongoing research will support a leapfrog to ultra-low-GWP refrigerants to limit emissions.

Future Research Priorities

Research will support the safe transition to climate-friendly HFC alternatives by evaluating the feasibility, performance, and impacts of options like HFOs and natural refrigerants. A key concern is that HFOs can break down into trifluoroacetic acid (TFA), which may accumulate in aquatic environments at higher rates than some HFCs.[117] HFOs and the impact of their degradation products, like TFA, are a topic of concern, and further study would inform

[116] CARB Contract 23RD021.

[117] *Cahill, Thomas M., et al. "Accumulation of trifluoroacetate in seasonal wetlands in California." Environmental science & technology 35.5 (2001): 820-825.*

mitigation options for HFCs.[118] Further study will clarify these risks, including toxicity, persistence in the environment, bioaccumulation, and potential health outcomes. This work is important to inform policies in California, as well as other jurisdictions.

- Are there HFO and HFC degradation products, and do they have any potential health and environmental impacts?

- What is the feasibility, performance, and safe use of climate-friendly HFC alternatives for heat pump technologies and other HFC sectors?

F. Wildfire Emissions in a Changing World and Impacts on Environmental Justice Outcomes

Californians are increasingly exposed to large, high-severity wildfires that damage property and infrastructure, worsen air quality, and contribute to climate change. Climate change and other environmental factors have created feedback loops that intensify the frequency and severity of these events, presenting significant challenges to CARB's air quality, health, and climate goals (see Figure 10). Burned areas in northern and central California have increased fivefold from 1996 to 2021 compared to the period from 1971 to 1995. In 2020 alone, wildfires resulted in over $19 billion in economic losses. Outdoor workers and overburdened communities with limited adaptive capacity can be disproportionately affected. These impacts underscore the importance of addressing wildfire smoke exposure through integrated public health and community resilience. In response, California is incorporating Tribal knowledge and traditional forest management practices into its fuel management strategies to help reduce wildfire risk and severity.[119]

Health concerns are also rising, especially in the wildland-urban interface (WUI), described as the transitional zone between unoccupied or undeveloped land and human development. In WUI, fires can destroy structures and release a complex mix of understudied air toxics. Smoke

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[118] Beringer et al., (2021). *Persistent degradation products of halogenated refrigerants and blowing agents in the environment: type, environmental concentrations, and fate with particular regard to new halogenated substitutes with low global warming potential*.

[119] *How the Indigenous practice of 'good fire' can help our forests thrive | University of California*.

from these fires often travels to nearby communities and compounding exposure to harmful air pollutants. Wildfire emissions also influence ozone and secondary organic aerosol (SOA) formation, though the full extent of these effects remains an area of active research.

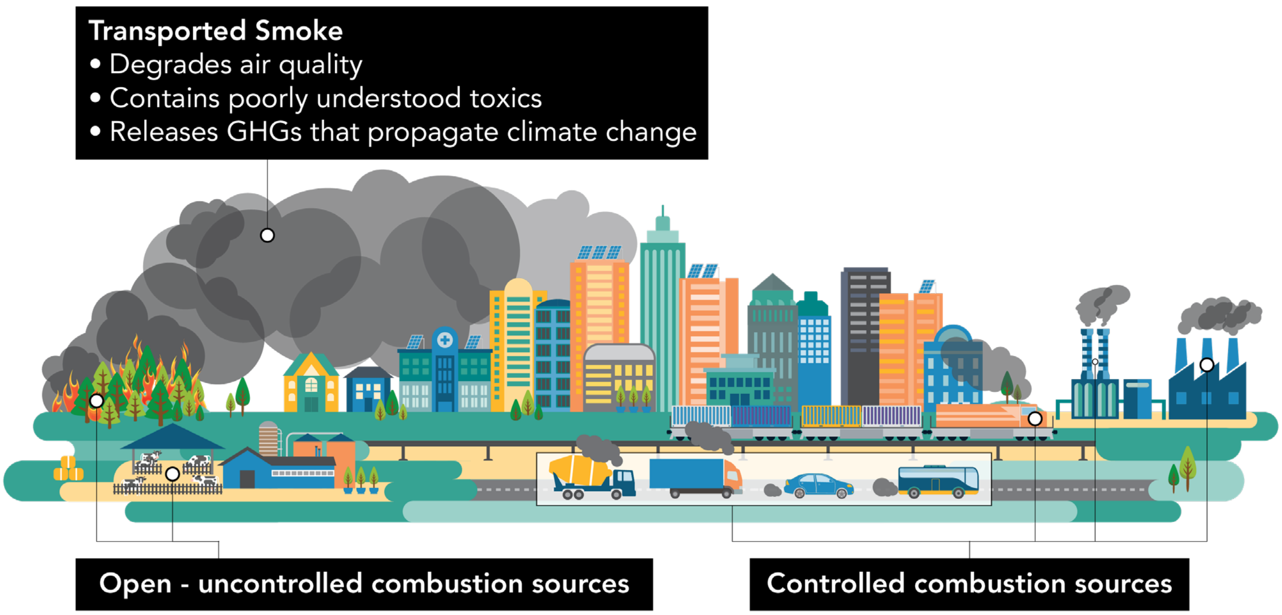

Figure 10: Wildfires are a large source of uncontrolled emissions that are increasing in severity due to climate change.

Past Research

A recent study[120] quantified emission factors for criteria pollutants, volatile organic compounds (VOCs), and selected air toxics from prescribed burns. Emissions were found to be similar across forests with different management histories. The research emphasized the importance of accurate fuel input data, such as litter, woody debris, and fuel loadings, for predicting emissions from both prescribed burns and wildfires. The results provide information for wildfire emission estimates and help understand the role of wildfires on ambient PM2.5 levels and the formation of secondary air pollutants.

[120] CARB Contract *19RD008*.

Current Research

Two projects will help improve the understanding of emissions and air quality impacts from wildfires and prescribed burns. One[121] will estimate emission factors and chemical speciation from burning structures typical of California's WUI, where mixed fuels (i.e., buildings and vegetation) and varied terrain contribute to intense fires and destruction. The results are expected to provide information on the release of toxic chemicals from burning metals, plastics, and other petroleum-based products. The second project[122] will evaluate the air quality impacts of wildfires and prescribed burning on downwind urban areas by analyzing, monitoring, and modeling data. The research will help CARB better understand the relative emissions, chemistry, and transport of smoke from wildfires versus prescribed burns and help address the *Wildfire and Forest Resilience Task Force Action Plan*.

Future Research Needs

Timely Drivers

SB 456 (Liard, Stats. of 2021, Ch. 387) requires California to develop and regularly update a science-based review and action plan to guide and inform regional strategies on actions needed to improve the community fire resilience plans. Updates to the action plan may have additional research needs that will drive CARB's research program over the next five years.

Under *SB 1260* (Jackson, Stats. of 2018, Ch. 624), CARB and the California Department of Forestry and Fire Protection (CAL FIRE), in coordination with local air districts, are directed to develop and fund a program to enhance air quality and smoke monitoring. The bill includes a public awareness campaign on prescribed burning and promotes long-term forest health and wildfire resilience through fire prevention and forestry management projects by CAL FIRE and federal land management agencies.

Smoke exposure is a community health concern, as highlighted in the recent Staff Report for the Community Air Protection Program recommendations for the South Sacramento Florin Community.[123] WUI communities are expected to face continued risks from smoke exposure and climate-driven wildfires in the future.

Future Research Priorities

Research will evaluate the impacts of fire emissions on climate and human health. A deeper understanding of wildfire plume rise, emission characteristics, long-range transport, and climate change effects will inform vulnerability to wildfires. Burn scars with fallen snags and

[121] CARB Contract *22RD004*.
[122] CARB Contract 23RD006.
[123] *CAPP Rec Staff Report FINAL 20240513.pdf*.

brush can release additional pollutants if re-burned, consuming regrowth and underbrush. The net carbon change from pre-first fire to subsequent burns remains uncertain. For health-related research on this topic, refer to the *Health Impacts of Climate Change and Wildfire Smoke* section.

While initial studies have assessed land management strategies, further research is needed to compare emissions from prescribed burns and uncontrolled wildfires. California has a goal to increase prescribed burning acreage to reduce pollution associated with high-severity wildfires.[124] As climate change alters fire behavior and regimes, this remains a critical area of ongoing research.

- What are the environmental, public health, and air quality impacts of burn scars, ash exposure, and how might these impacts change future wildfire scenarios?
- How will fire emissions change as the severity and location of wildfires increase due to climate change?
- What are the potential climate, air quality, and health outcomes under different wildfire scenarios?
- How can we quantify spatial variability in forest structure before and after fires, and how might this influence patterns of wildfire severity?
- How can we better predict fire dynamics at a more local level?

- What research is needed to understand the impact of wildfires on the WUI and associated communities?
- What preventative measures can support frontline and vulnerable communities in protecting themselves from the effects of wildfire emissions?

- What are the potential air quality and health impacts of different scenarios for prescribed burning?
- How do fire emissions change on large spatial and temporal scales when prescribed burning is adopted on a wide scale?

[124] *Assembly Bill 642*.

Research Highlight: Prescribed Burns & Wildfire Risks

Prescribed burns are used to reduce the spread and intensity of wildfires. Prescribed burns decrease the build-up of biomass fuel, or grasses and vegetation that feed wildfires. A **CARB-funded project** collected air samples during a four-day prescribed burns to improve upon a fire model that can be used to predict smoke emissions from prescribed burns and wildfires.

What was found?

- Accurate fuel loading data, such as the amount of litter or woody debris, is crucial to making reliable fire emissions predictions.
- Understanding the emission levels from biomass burning also improves health & climate predictions.

Why is this work important?

- Prescribed burns can be an effective way to reduce biomass fuel, which is vital for reducing fire severity.

How will results be used?

Results provide a valuable resource and database for CARB to protect public health, improve statewide fire emission estimates, and lessen wildfire risks.

G. Climate Change Impacts on Health, Economics, and Other Factors

Over the last 20 years, California has passed legislation to reduce GHG emissions and the impacts of climate change. As sources of GHGs are typically sources of criteria pollutants, many GHG reduction efforts also improve air quality. Effects of wildfires, extreme heat, drought, flooding, and other climate change impacts may worsen air quality, a phenomenon known as the climate penalty. Rising temperatures, for example, can increase ozone levels despite reductions in NOx and VOCs, potentially offsetting progress and requiring more stringent emissions reductions to meet NAAQS. The extent of the climate penalty on future air quality impacts is still an open research question.

Future Research Needs

Timely Drivers

AB 1279 sets targets for California to achieve carbon neutrality by 2045 and reduce statewide GHG emissions to 85% below 1990 levels by 2045. The bill requires the Scoping Plan to identify measures to achieve carbon neutrality and recommend policies that support carbon dioxide removal through carbon capture, utilization, and storage technologies, in addition to reducing GHG emissions from the source. Achieving carbon neutrality will slow global warming and benefit air quality and ecological recovery. Continued research on these co-benefits will help inform future policy and research priorities.

Future Research Priorities

- How will climate change impact air quality in the future?
- Will it significantly impact ozone, volatile organic compounds, PM, and NOx emissions?
- How will climate impacts, like extreme heat, soil aridification, flooding, and other outcomes, worsen air quality?

- What are the co-benefits of air quality and climate strategies?

- What are the economic, health, and other impacts of climate change on the state and communities within California?

H. Equitable Transition to a Low-Carbon Future

Protecting communities is a consideration for climate change programs since climate change may increase disparities in air pollution exposure. While the transition involves costs, the state seeks to reduce burdens on consumers and considers the costs of inaction on communities. These issues are addressed in the 2022 Scoping Plan and the California Energy Commission's Climate Change Assessment.[125]

Future Research Needs

Timely Drivers

AB 32 established statewide GHG emission limits to 1990 levels by 2020 and authorized CARB to use market-based mechanisms to reach that objective. *SB 535* (De León, Stats. of 2012, Ch. 830) required at least 25% of the Greenhouse Gas Reduction Fund investments to benefit communities identified through CalEnviroScreen 2.0. *AB 2722* (Burke, Stats. of 2016, Ch. 371) later created the *Transformative Climate Communities Program*. More research will help develop strategies and tools to support communities.

Future Research Priorities

- What research can aid in understanding the benefits of local GHG emission reduction opportunities, such as vehicle-miles traveled reduction, urban forestry, and strategic land use planning?

- As part of ongoing assessments, how do we collect data to understand the co-benefits of climate strategies?
- What research on cumulative environmental and social impacts would be most beneficial to support equitable decision-making?
- What data is most needed for future Scoping Plan development?

[125] *California's Fourth Climate Change Assessment*.

Chapter 4: Mobile Sources Research

A. Introduction

CARB regulates emissions from mobile sources operating within California, including vehicles or equipment registered out of state. Mobile sources include light-duty vehicles (LDV), heavy-duty vehicles (HDV), and off-road equipment (ORE). They emit the majority of smog-forming oxides of nitrogen (NOx), represent the largest share of greenhouse gas (GHG) emissions, and are a major source of toxic air contaminants that pose serious health risks to communities. Recognizing their substantial impact on air quality and climate, CARB's Research Program has long prioritized research on mobile sources. While the focus is on California, many of the research findings have broader relevance and can inform efforts in other jurisdictions.

CARB's Research Program is guided by California's commitment to achieving multiple air quality and climate goals, including attainment of the National Ambient Air Quality Standards (NAAQS), reducing public health risk from toxic air contaminants, and meeting statewide GHG and air pollution reduction targets.

As existing regulations continue to reduce tailpipe emissions, CARB's research is evolving to address emerging issues associated with advancing vehicle technologies and shifts in the mobile sources emissions inventory. An example is brake- and tire-wear (BWTW) emissions, which have become the leading source of directly emitted PM2.5 from on-road mobile sources. Technologies such as regenerative braking present potential opportunities to reduce both brake-wear PM and certain gaseous emissions, offering additional air quality benefits. Research on these topics can inform zero-emission vehicle (ZEV) and incentive programs that promote the adoption of regenerative braking and low-drag friction brake technologies.

Continued investment in mobile sources research ensures that CARB's emission reduction programs are informed by robust scientific evidence while considering co-benefits to California's public health, environment, and economy.

How is Mobile Sources Research Used at the California Air Resources Board?

Results from CARB's research have informed both state and national emission reduction programs. A low-NOx technology demonstration project[126] showed that tailpipe NOx emissions from heavy-duty vehicles can be reduced by 90% or more without increasing GHG emissions. This research informed the development of the low-load cycle (LLC) that better

[126] CARB Contract *13-312*.

represents real-world driving conditions and directly supported the implementation of the Heavy-Duty Engine and Vehicle Omnibus Regulation.

Building on the success of its low-NOx research[127] in the on-road sector, CARB expanded its efforts to the off-road engines,[128] which contribute approximately 14% of statewide NOx emissions and 29% of diesel PM emissions. This research demonstrated that NOx emissions could be reduced by 90% and PM emissions by 75% below the current Tier 4 standards, providing a strong technical foundation for the development of new Tier 5 standards. CARB's mobile sources research has also advanced the understanding of non-exhaust emissions, particularly brake-wear PM. These findings were incorporated into the 2021 update of CARB's *on-road emission inventory* (EMFAC).[129, 130]

B. Long-term Trends in Oxides of Nitrogen and Greenhouse Gas Emissions

Research on long-term emissions trends has focused on monitoring real-world emissions from both light- and heavy-duty on-road vehicles to improve our understanding of in-use performance and high-emitting vehicles. This research has helped track the effectiveness of in-use fleet rules (e.g., Drayage and Truck and Bus rules) and programs (*Heavy-Duty Vehicle Inspection Program* and the *Periodic Smoke Inspection Program*) that aim to reduce emissions from heavy-duty trucks. Long-term emission monitoring strategies include the use of Portable Emission Measurement Systems (PEMS), remote sensing technologies, and plume capture techniques.

Past Research

Plume capture methods have been used to sample exhaust from passing HDVs at four field sites in California to assess the effectiveness of in-use fleet rules.[131] The results show substantial reductions in tailpipe NOx and black carbon (BC) emissions. These reductions are largely attributed to the turnover of pre-2010 model year (MY) diesel engines to newer heavy-duty diesel trucks, as well as the retrofitting of pre-2010 MY engines with after-treatment technologies (Figure 11), as mandated by the Drayage Truck Rule and the *Truck and Bus Regulation*.

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[127] CARB Contract *13-312*.

[128] CARB Contracts *18RD006* and *19RD025*.

[129] CARB Contract *17RD016* and CalTrans Contract 65A0703.

[130] CARB Contract *18RD017*.

[131] CARB Contracts *12-315* and *14-358*.

Research Highlight: Lowering NOx using Today's Technology

NO_X is produced when burning fossil fuel and is released from the tailpipe of internal combustion engine vehicles. NO_X emissions from large diesel engines needed to be further reduced beyond existing standards to meet National Ambient Air Quality Standards. A previous **CARB project** focused on finding ways to lower NO_X emitted in compressed natural gas- and diesel-based heavy-duty vehicle engines.

Results led to a **follow-up project**, which tested two off-road engines fitted with different aftertreatment systems.

What was found?

They successfully created an aftertreatment configuration that reduced NO_X by 90% for heavy-duty vehicles and reduced NO_X and particulate matter by 90% and 75%, respectively for off-road engines.

Why is this work important?

Shows today's technology can be used to achieve ultra- low NO_X emissions which will help improve air quality.

How were results used?

It led to the creation of regulations at the **State** and **Federal** level currently being used to reduce emissions.

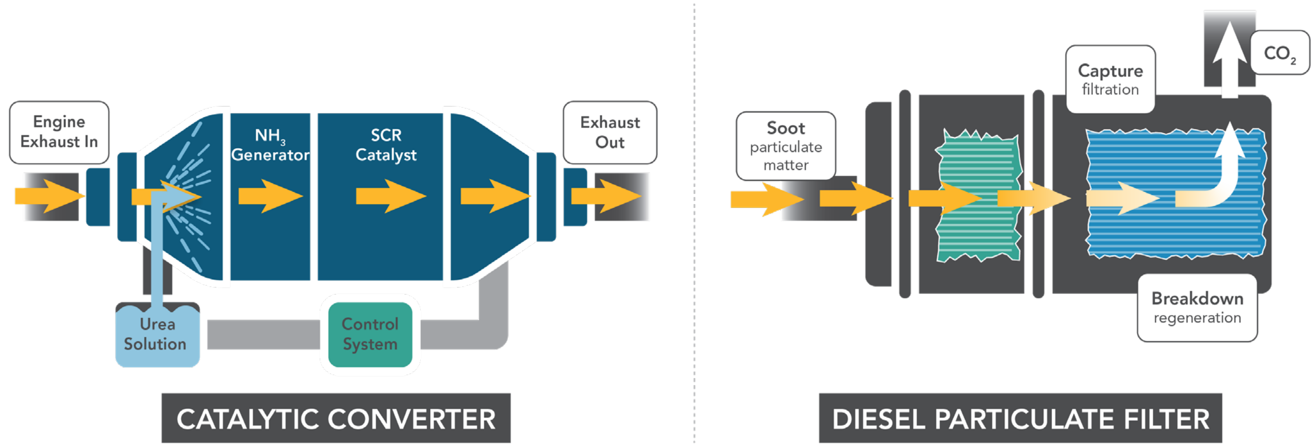

Figure 1111: *Diesel particulate filter (DPF) on a diesel engine to reduce engine-out particulate matter emissions* (left diagram) and a *selective catalytic reduction (SCR) system* designed to reduce engine-out NOx emissions by reacting with ammonia (NH_3) generated from a urea-based diesel exhaust fluid (DEF) solution (right diagram).

CARB has also evaluated NOx and GHG emissions from in-use heavy-duty diesel vehicles (HDDVs) using various data sources, including Portable Activity Measurement Systems (PAMS), PEMS, and chassis dynamometers (Figure 12).[132] These evaluations show that tailpipe NOx emissions have declined with MY 2010 and newer engines, aligning with the adoption of stricter regulations like the Heavy-Duty (HD) On-Board Diagnostic (OBD) standard. However, NOx emissions under low-load conditions continue to exceed engine limits, underscoring the challenge of controlling real-world emissions from heavy-duty vehicles.

Current Research

CARB recently completed three plume-capture measurement campaigns at the Caldecott tunnel to assess in-use emissions from heavy-duty diesel trucks.[133] The latest campaigns ended in September 2023, the first year when all on-road heavy-duty diesel trucks had to be equipped or retrofitted with selective catalytic reduction (SCR) and DPF systems. Results indicate widespread adoption of SCR (98% of the fleet) and DPF (>99% of the fleet) systems, but also highlight issues with poor maintenance and a growing share of emissions coming from a small subset of high-emitting vehicles. To further investigate high in-use emissions from both heavy-duty diesel and natural gas trucks, CARB launched two research contracts[134] utilizing cost-effective on-board sensors for NOx, PM, NH_3, and CO_2. These studies aim to identify the causes of elevated emissions, including component degradation, insufficient

[132] CARB Contracts *13-301*, *14-302*, and *16RD012*.
[133] CARB Contract *20RD004*.
[134] CARB Contracts *21RD007* and *21RD018*.

maintenance, and tampering. In addition, CARB's Enforcement Program uses the PEAQS to detect high-emitting trucks.[135] The PEAQS continues to support enforcement efforts and offers potential for expanded use in future research initiatives.

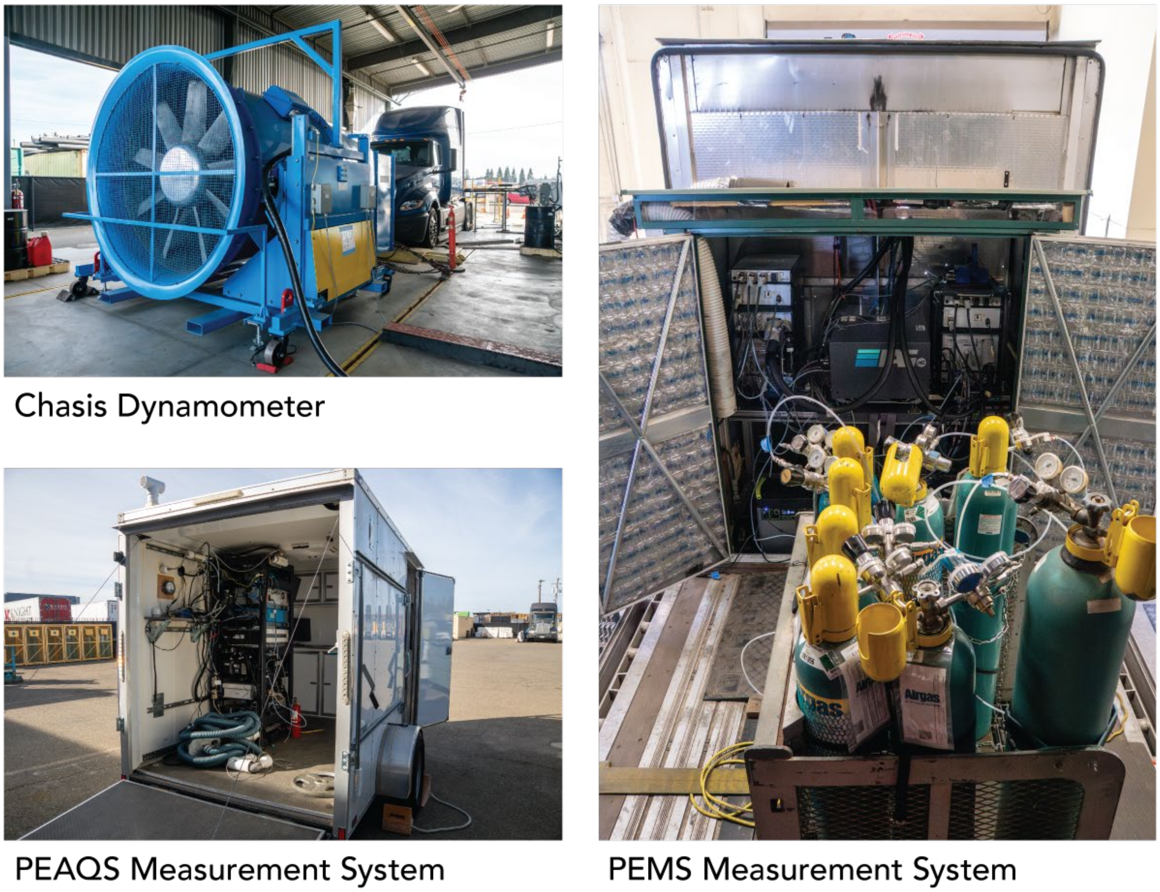

Figure 1212. Photographs of a heavy-duty vehicle being tested on a chassis dynamometer, Portable Emissions Acquisition System (PEAQS), and the PEMS testing setup on a heavy-duty vehicle.

Future Research Needs

Timely Drivers

Moving forward, various upcoming regulatory milestones will influence vehicle emissions and fleet turnover. The most recently proposed amendments to the HD OBD regulations[136] aim

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[135] *CARB deploys 'Dirty Truck Detector' along popular Fresno truck route | California Air Resources Board*.
[136] *2021 Notice Register Number 23-Z, June 4, 2021 (ca.gov)*.

to improve data reporting and tracking, NOx monitoring, and tracking of catalyst malfunctions, among other things, for most 2027 MY vehicles. If adopted, these changes can facilitate more effective monitoring of on-road vehicle emissions.

California's Truck and Bus Rule, HD Inspection and Maintenance (I/M) Program, and clean transportation initiatives are expected to significantly reduce GHG and other tailpipe emissions while delivering hundreds of billions of dollars in fuel cost savings. New research on durable emission control systems, energy-efficient vehicle technologies, and their role in advancing the adoption of ZEV can support efforts focused on improving local and regional air quality while reducing GHG emissions. Although centered on California's goals, this research can also inform and support similar efforts in other jurisdictions.

Future Research Priorities

As more ZEVs are deployed, in-use emissions profiles are expected to shift. Ongoing research can track these changes and inform updates to CARB's emission inventory. Monitoring real-world emissions can also help assess program effectiveness and identify opportunities for further mitigation. High-emitting vehicles remain a concern, particularly in overburdened communities, where issues such as idling are still frequently reported. Elevated emission rates may result from factors such as SCR deterioration, tampering, or unfiltered exhaust leaks.

- What are the real-world in-use emissions trends of GHG and criteria pollutants from on-road vehicles, and how do regulatory programs impact them?
- How can data from PEAQS and the Clean Truck Check be leveraged to track these emission trends?

- What are effective ways to measure and identify high-emitters, and how many repeat measurements are needed?
- What fraction of heavy-duty vehicles may malfunction, have deteriorating SCRs, or leak unfiltered exhaust?
- Can we quantify those emissions and their potential impacts on communities?

C. Advances in Mobile Sources Monitoring

On-board NOx sensors can track SCR performance and gather emissions data across a broad range of operating conditions. Current designs struggle with accuracy at low temperatures (e.g., during low-load or idle) and at low NOx levels expected from future engine technologies. CARB is exploring cost-effective on-board sensors for air pollutants like CO_2, NOx, PM, and NH_3, and developing algorithms to improve sensor accuracy. This work can enhance real-world emissions monitoring, support updates to emission inventories, and provide scalable tools that could be adopted by other states and jurisdictions.

Past Research

CARB conducted an in-house analysis of NOx emissions using on-board sensor data collected through multiple research projects.[137] The results suggest that in-use NOx emissions from HDDVs across several locations consistently exceeded emissions standards, even when the SCR systems were operating within their optimal temperature range for NOx reduction. These results suggest catalytic degradation issues on some engines.

Current Research

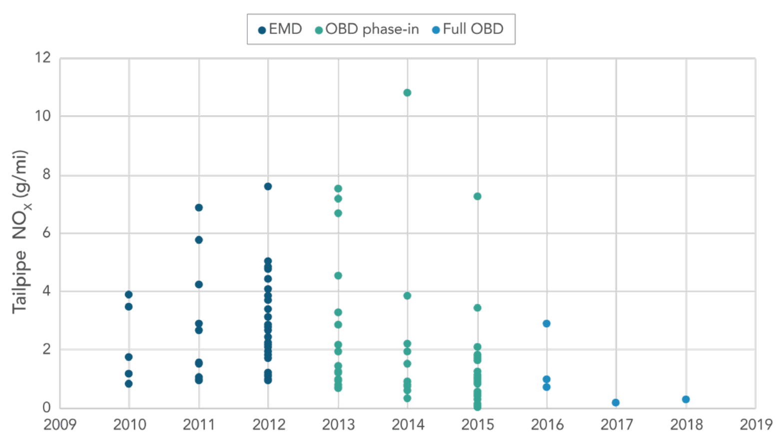
A current CARB research project[138] is evaluating the sensitivity, accuracy, and durability of advanced on-board sensor technologies for measuring NOx, PM, NH_3, and CO_2 emissions at levels relevant for future low-emission limits. The project focuses on measuring NOx emissions at levels below 10 parts-per-million (ppm). This project also investigates the performance of laser-based tailpipe sensors, which are less susceptible to measurement artifacts and interference. Additional studies are being conducted to improve their performance.[139]

Recent findings from a large monitoring study[140] suggest that some HDVs may leak unfiltered exhaust during high-load operations, likely due to poorly maintained after-treatment systems. This raises concerns about increased community exposure to harmful air pollutants and presents challenges for meeting air quality standards. CARB is investigating this issue using rapid detection methods to identify vehicles with exhaust leaks.[141] Findings from this research are expected to inform emission inventories and the Clean Truck Check program. While the initial findings are based on vehicles operating in California, they are relevant to similar fleets in other jurisdictions and can help guide national and regional efforts to reduce emissions.

[137] CARB Contracts *16RD012*, *13-301*, and *14-302*.
[138] CARB Contract *21RD007*.
[139] CARB Contract 22RD009.
[140] CARB Contract *16RD012*.
[141] CARB Contract *23RD009*.

Research Highlight: Using Monitors to Understand Heavy-Duty Emissions & the Impact of Regulations

CARB monitors emissions from on-road heavy-duty vehicles by collecting data from moving vehicles.



What was found?

This method worked well to identify vehicles with high NO_X emissions.

Future work will address the need to improve data collection when engine temperatures are low.

CARB regulations reduced NO_X emissions from heavy-duty vehicles.

Why is this work important?

Collecting data from moving vehicles shows how CARB regulations impact emissions from heavy-duty vehicles across the state, including those traveling through priority communities.

CARB's in-house project examines the pros and cons of using real-world data to track emissions.

How will results be used?

To update CARB's emission inventories, evaluate existing emission control measures, and develop future strategies to reduce emissions.

Future Research Needs

Timely Drivers

Upcoming regulatory milestones will require engines to achieve lower emissions of NOx, PM, and other criteria pollutants. This transition may increase the need for more advanced emissions monitoring techniques, particularly the development and deployment of onboard sensors. In addition, more stringent NAAQS, such as the U.S. EPA's new annual PM2.5 standard of 9 $\mu g/m^3$, may further drive research toward the use of more advanced measurement tools in research.

Future Research Priorities

On-board sensors and OBD present a cost-effective and efficient opportunity to monitor vehicle emissions and performance in real-time. Further research and development are needed to enhance their accuracy, reliability, and broader applicability.

- Can more emissions be monitored and reported through OBD, and what data quality can be achieved?
- Can we improve the performance and reliability of existing onboard sensors?
- For low-NOx engines, are the current sensors sensitive enough?
- Is OBD data adequate for the enforcement of CARB regulations?

- What opportunities exist to track important OBD parameters from ZEV?

- How do we utilize HD I/M data, including OBD scans, to track in-use emissions?
- How can it be linked with real-time HD in-use emissions data?
- How do we leverage the reporting data?
- Can we bridge all the reporting data to learn something new?

- Can this data be used to track failure and repair rates and to track the overall impact on emissions?

D. Understanding Mobile Source Emission Disparities

Past Research

Light-duty vehicle (LDV) exhaust emission rates were measured using roadside-deployed remote sensing devices (RSDs) in West Los Angeles between 1999 and 2018.[142] CARB staff conducted an in-house analysis to explore the potential relationship between emission rates and the socioeconomic status of the communities where the vehicles were registered. The analysis[143] suggests that vehicles registered in socioeconomically disadvantaged communities (DAC) exhibited higher emission rates of CO, HC, and NO than those registered in non-DAC areas within the Greater Los Angeles area.

Current Research

CARB is conducting a larger-scale RSD measurement study across eight locations in California.[144] Preliminary results indicate that vehicles registered in communities designated as DAC under SB 535[145] emit significantly higher levels of air pollutants compared to those registered in non-DAC areas. Differences in vehicle model year can be used to explain approximately 30% and 48% of this emissions disparity. Higher vehicle emissions in DACs can contribute to increased exposure and associated health risks for these communities. Long-term, spatially extensive data is important for future emission reduction programs and the Community Air Protection Program (CAPP).

Future Research Needs

Timely Drivers

The *CAPP Blueprint 2.0* outlines the state's five-year strategy, including recommendations on mobile sources. Community-focused research on mobile source emissions is important for developing targeted strategies to reduce air pollutant exposure. For example, a recent report on emission exposure disparities near the California-Mexico border[146] provided updated emissions analysis and actionable recommendations.

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[142] CARB Contracts *07-319*, *12-303*, *17RD015*, and *20RD001*.

[143] Zhan et al., An Assessment of the Impact of Socioeconomic Status (SES) on Light-duty Vehicle Emission Characteristics. 29th CRC Real-World Emissions Workshop, Long Beach, CA March 11-13, 2019.

[144] CARB Contract *20RD001*.

[145] *Final Designation of Disadvantaged Communities Pursuant to SB535, 2022*.

[146] *Baja_California_Fleet_Characterization_ERG_Final_Report_021323.pdf*.

Future Research Priorities

- How can CARB's RSD research be used to continue understanding emissions disparities?
- Can a longitudinal study be leveraged to understand the long-term impacts of programs like CAPP?
- Can further analysis be done to understand the impact of goods-delivery activities versus private vehicle ownership?
- Can continued RSD measurements be leveraged to track community-level emission rates and assess total emissions in communities?

- What is the regional and local impact of emissions from legacy vehicles and vehicles needing maintenance, particularly in communities?

E. Activity and Vehicle Energy Analysis

Several demonstration and pilot projects have successfully shown that zero-emission (ZE) HDVs can match the performance requirements of their conventional counterparts in select vocations. However, widespread adoption through new sales and fleet turnover will take time. In the meantime, it is important to characterize ZE HDVs' activity, energy demand, and charging patterns under real-world operation.

Past Research

Two projects[147] are focused on collecting and analyzing activity data for agricultural and construction equipment, which is an important step in updating emissions inventories and informing regulation development in the off-road sector.

A recent project[148] also assessed the current electrification trends within the off-road sector and determined the factors behind these trends, providing CARB with a potential roadmap for future incentive programs aimed at advancing air quality and climate goals.

[147] CARB Contracts *17RD013* and 19RD002.
[148] CARB Contract *18RD016*.

Current Research

A ZEV energy efficiency review study[149] is assessing electric vehicle systems and component technologies that could improve energy efficiency or reduce brake-wear and tire-wear (BWTW) emissions for passenger cars, trucks, and off-road equipment (ORE). Findings from this project can support updates to emissions inventories and inform ZEV programs and policy development. The ZEV data logging project proposed in 2024 aims to characterize real-world ZEV activity, energy consumption, charging behavior, air quality co-benefits, and disparities in air pollution burden associated with the reductions in GHG and air pollution emissions from ZEV adoption.

The Alternative Charging Solutions (ACS) project is designed to characterize activity patterns, energy use, emission reductions, and cost-effectiveness of off-grid charging solutions for California's ZE ORE. Findings from this research can inform expanding ORE electrification strategies in alignment with Executive Order N-79-20 and California's air quality and GHG reduction goals. This research will also investigate the most cost-effective ZE ORE and ACS pathways to inform the potential *Phased Advanced Clean Equipment (PACE)* requirements. Similar efforts outside of California may benefit from such insight into energy efficiency, real-world energy consumption, charging needs, and associated costs and benefits.

Future Research Needs

Timely Drivers

Future research in this area can inform a range of heavy-duty on-road and off-road clean transportation programs.

Future Research Priorities

- What are the conventional and various ZEVs' operational characteristics and detailed energy consumption rates, including transit and commuter buses, off-road vehicles, heavy-duty and medium-duty vehicles, and passenger vehicles?
- What are the charging behaviors of these vehicles, and can that information be leveraged in statewide efforts to optimize infrastructure?
- What are the operational characteristics of plug-in hybrid electric vehicles (PHEV), including driver behavior, driving, and charging patterns, that would lead to data-driven recommendations to increase PHEV electric vehicle-miles-traveled (VMT)?

[149] CARB Contract 23RD007.

- What are the impacts on ZEVs of existing and emerging technologies associated with vehicle-level efficiency, including climate control, regenerative braking, low-rolling resistance tires, and others?
- Can we demonstrate emerging technologies and opportunities to reduce impacts further?

F. Controlling and Monitoring Off-Road In-Use Emissions

ORE, such as those used in construction, mining, and industrial operations, contribute significantly to California's NOx emissions. The off-road sector is responsible for about 14% of statewide NOx emissions, making it California's second-largest mobile source of NOx in the state. Many mitigation strategies are being considered to reduce emissions from ORE, including the deployment of advanced monitoring technologies, the development of cleaner engines and after-treatment systems, and the adoption of ZE equipment. These efforts support California's broader goals of meeting increasingly stringent environmental standards and achieving GHG reduction targets.

Past Research

Technology innovation projects[150] have explored emissions reductions from off-road diesel engines by designing and optimizing advanced NOx and PM after-treatment technologies to meet current and proposed emission standards, such as the proposed Tier 5 emission standards. Refer to the *Activity and Vehicle Energy Analysis* section for additional information on ORE-related projects.

Current Research

A ZEV energy efficiency review study[151] is assessing electric vehicle systems and component technologies that could improve energy efficiency or reduce BWTW emissions for passenger cars, trucks, and ORE. Refer to the *Activity and Vehicle Energy Analysis* and *Advances in Mobile Sources Monitoring* sections for projects associated with ORE, energy efficiency, and on-board sensor technology.

[150] CARB Contracts *18RD006* and *19RD025*.
[151] CARB Contract 23RD007.

Future Research Needs

Timely Drivers

Research on ORE can inform the development of future emissions standards and support the transition to ZE technologies. As new technologies are adopted and more ORE comply with Tier 4 final emission standards and beyond, additional field testing and ORE activity data analysis may become more important for refining emissions estimates and updating inventories.

Future Research Priorities

Current research has examined the long-term trends in NOx, GHG emissions, and fuel economy from off-road engines to assess alignment with certification standards. Continued research can help track progress toward meeting upcoming emission requirements. Additionally, more comprehensive data on off-road mobile source activity and emission rates, especially for primarily federally regulated sources such as aircraft, locomotives, and ocean-going vessels, can support regulatory programs and emission inventory updates.

- As new technologies are adopted, are they meeting more stringent certification standards in real-world applications?

- What vocations and vehicle types can be characterized to improve the emissions inventory?
- Which sectors will further our understanding of the impact of off-road vehicles on local and regional air quality?

- How can we continue to encourage zero-emission technology adoption in the off-road sector, and what are the energy demands by vocation?
- What vocation types can adopt zero-emission technologies effectively?

G. Incentives, Zero Emission Vehicles, and Charging Infrastructure

CARB has adopted and implemented *Advanced Clean Cars* programs to reduce emissions from light-duty vehicles starting with the 2012 model year. Advanced Clean Cars programs increase ZEV sales requirements and tighten standards for gasoline-powered vehicles to meet California's goal of carbon neutrality by 2045. Accelerating the adoption of zero-emission technologies while reducing emissions from conventional vehicles will produce substantial public health benefits by reducing premature deaths, hospitalizations, and lost workdays associated with exposure to air pollution.

Past Research

CARB has expanded its incentive programs to promote the purchase of ZEVs. As ZEVs become more widespread, ensuring equitable access to incentives and evaluating the effectiveness of charging infrastructure have emerged as key research priorities.

To understand the benefits of used ZEVs in the secondary market, a recently completed project[152] compared owners of used ZEVs to those of new ZEVs and both new and used internal combustion engine vehicles. The findings provide valuable insights to inform future program design, support California's ZEV adoption goals, and address health and opportunity disparities across communities. These insights may also be applicable to ZEV programs in other states and jurisdictions.

Current Research

CARB is funding several research projects focused on ZEV incentives, adoption, and infrastructure. One project[153] is assessing ZEV planning efforts across California and developing resources to support equitable, multi-modal ZEV systems. CARB also funded a project[154] to develop a quantitative and qualitative evaluation framework of feasible Recycled Content Standards (RCS) for automotive traction batteries in California. CARB is also supporting research[155] to better understand the transportation needs of underserved communities and how ZEVs can cost-effectively meet these needs. An additional project[156] is investigating who buys used ZEVs and examining community readiness, barriers, and best practices to support the state's ZEV adoption goals.

Future Research Needs

Timely Drivers

Future research will focus on equitable access and effective messaging to boost participation and support similar programs in other regions. CARB is also partnering with the California

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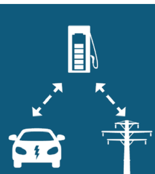
[152] CARB Contract *22STC016*.
[153] CARB Contract 22STC012.
[154] CARB Contract 23STC027.
[155] CARB Contract *22STC017*.
[156] CARB Contract 22STC016.

Public Utility Commission (CPUC) on research related to charging accessibility and grid capacity to ensure alignment with California's climate goals.

Future Research Priorities

- What opportunities are there to decarbonize the total lifecycle emissions of zero-emission vehicles?
- What are the costs and benefits of recycling battery materials compared to new production?
- What approaches reduce any potential unintended impacts of battery production and recycling?
- What research can help increase battery recycling and reuse?



- What is the consumer interest and propensity to use Vehicle-to-Everything (V2X) technologies, including pricing structures to induce the use of battery-electric vehicles to provide power to their homes or the grid?

H. Improving Understanding of Non-Exhaust Emissions

As exhaust PM emissions have decreased significantly due to stringent tailpipe emission standards, non-exhaust sources such as brake-, tire-, and wheel-wear have emerged as the main contributors to direct PM2.5 emissions from on-road mobile sources. With VMT continuing to rise and tailpipe emissions decreasing further, the contribution of BWTW emissions is expected to grow. PM from BWTW has been studied for its oxidative stress potential, which is linked to cardiovascular and respiratory diseases, as well as increased cancer risks, highlighting the importance of continued research on BWTW.[157] As shown in Figure 13, brake-wear PM has already exceeded exhaust PM2.5 emissions in 2020, and tire-wear PM2.5 emissions are projected to exceed exhaust PM2.5 emissions by 2035.

Aside from PM, non-exhaust emissions contain substantial gaseous compounds that may be toxic to humans and contribute to the formation of secondary PM. Significant knowledge gaps remain in understanding these emissions.

[157] CARB Contract *17RD012*.

Research Highlight: Brake-Wear Emissions

What was found?

Researchers measured brake- wear particulate matter emission factors for light-duty and heavy- duty vehicles using laboratory tests designed to represent real- world driving scenarios specific to California.

Why is this work important?

Non-exhaust emissions are an emerging source of pollution that has greater impacts on communities near roadways, which are mainly priority communities.

How will results be used?

To update CARB's emissions inventory, assess the co-benefits of current mobile source programs, and inform in assessing near- roadway community exposure and health effects.

Particulate matter emissions produced from using brakes will continue to rise if the amount miles traveled in California increases. Laboratory brake dynamometer tests were performed on cars and trucks in two different projects, **one for CARB** and **one for Caltrans**.

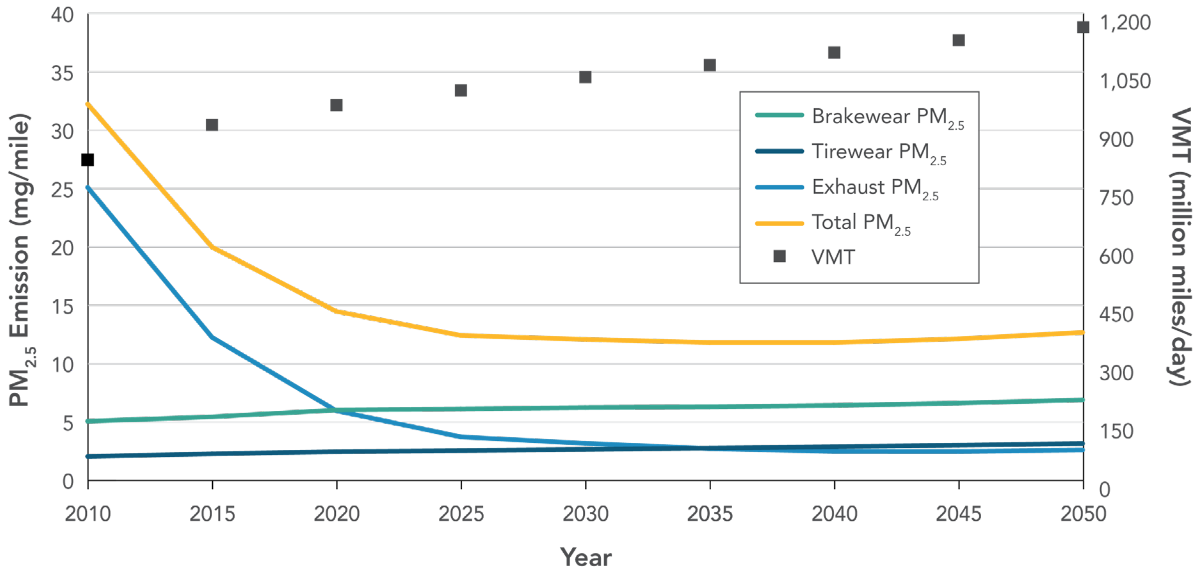


Figure 13: Time series of vehicle miles traveled and fine PM (PM2.5) emissions from brake-wear, tire-wear, and exhaust estimated using the EMFAC2021 model for 2010 to 2050.

Past Research

CARB,[158] the California Department of Transportation, and the U.S. EPA jointly benchmarked the European Joint Research Center's brake dynamometer cycle development procedure[159] and measured brake-wear PM formed during braking events for seven LDVs and five HDVs. Results from these projects were used to update brake-wear PM emissions in CARB's latest EMFAC2021. Subsequent studies examined the impact of non-exhaust PM in the real-world setting.[160]

Current Research

A current study[161] is focused on on-road BWTW emissions using novel sampling protocols. This research aims to understand the impact of vehicle electrification on emissions and inform relevant health impact assessments and programs. Emissions from California-representative

[158] CARB Contract *17RD016.*

[159] *ECE-TRANS-WP.29-2023-79E_0.pdf.*

[160] CARB Contract *18RD017*.

[161] CARB Contract *22RD002*.

LDVs and HDVs powered by gasoline, diesel, and electricity will be investigated. An upcoming project[162] will characterize gaseous emissions from tire-wear of on-road vehicles.

A recent project[163] focuses on characterizing brake-wear and wheel/rail-wear (BWWW) PM emissions from trains to identify the key factors influencing these emissions across different train types (e.g., line-hauls, switchers, and passenger trains) in California. The goal is to help address air quality concerns in near-railroad communities. In addition, a newly proposed project will investigate brake-wear emissions from off-road vehicles. This research will characterize brake-wear PM2.5, PM10, and gaseous emissions based on the duty cycles of various off-road vocational vehicles, including detailed chemical speciation.

The results of these studies can inform updates to the emission inventories, support air quality planning and community air protection efforts, help off-road emission reduction programs, and improve understanding of potential health impacts on nearby communities.

Future Research Needs

Timely Policy Drivers

Legislation like AB 844 (Nation, Stats. of 2003, Ch. 645)[164] and SB 346 (Kehoe, Stats. 2010, Ch. 307)[165] is driving changes in the materials used in brakes and tires. Since brake pads and tires are designed to wear down during use, their material composition directly affects the characteristics of BWTW emissions. Manufacturers have reformulated materials in response to these regulations, but their specific formulas are proprietary. Therefore, new measurements of BWTW emissions may be needed to reflect these changes. Additionally, emerging regulations in Europe and other major markets will influence the types of brake materials entering the California market. Under these shifting conditions, creating responsive research projects that track emissions and regularly provide updates to the emissions inventory is important.

[162] CARB Contract *23RD008*.
[163] CARB Contract *23RD010*.
[164] See also *Framework of California's Replacement Tire Efficiency Program | California Energy Commission*.
[165] See also *Limiting Copper in Brake Pads | Department of Toxic Substances Control*.

Future Research Priorities

- What are the real-world non-exhaust emissions and their health effects from various vehicle types, including LDVs, MDVs, HDVs, trains, and off-road vehicles on paved and unpaved roads, and various vocations, including construction, transit, agriculture, passenger, goods movement, etc.?

- Do non-exhaust emissions have regional and/or local impacts?
- Which pollutant emissions are of greatest concern?
- Do volatile organic compounds from non-exhaust emissions have the potential to contribute to secondary PM on a regional scale?
- For the larger PM fraction, do pollutant emissions affecting soil and water quality have potential downstream impacts on air quality?
- How do emissions negatively impact communities, particularly those near major roadways?
- Do these emissions impact indoor air quality? And are these emissions impacting exposure at a very localized level?

- What potential technological opportunities exist to reduce non-exhaust emissions from various vehicle types and vocations?
- Can ZEV technology reduce these emissions?

Chapter 5: Sustainable Transportation, Housing, and Communities Research

A. Introduction

Senate Bill 375 (Steinberg, Stats. of 2008) supports California's climate goals by encouraging regional planning efforts that integrate transportation, housing, and land use strategies to reduce greenhouse gas (GHG) emissions from passenger vehicles. While many regions have identified strategies to reduce vehicle-miles-traveled (VMT), the *2022 SB 150 Progress Report* indicates limited real-world progress, particularly in overburdened communities. This underscores the importance of continued research to support future implementation and help the state achieve its health and climate goals while avoiding the costs of inaction.

CARB collaborates with other state agencies to help align housing policy with California's climate goals. In parallel, CARB is advancing building decarbonization through initiatives such as the *Zero-Emission Space and Water Heater Standards* and efforts to reduce *embodied carbon*. Pursuant to *AB 2446* (Holden, Stats. of 2022, Ch. 352), CARB is developing a framework to reduce GHG from the building sector by 40% by 2035.

How is Sustainable Communities and Transportation Research used at the California Air Resources Board?

CARB's research on sustainable communities, housing, and transportation supports implementation of *SB 375* (Steinberg, Stats. of 2008, Ch. 728) through work on target-setting, *Sustainable Communities Strategy (SCS) guidelines*, and *SB 150 reports*. These projects provide data, modeling, and case studies that inform policy decisions and guide Metropolitan Planning Organizations (MPOs) and other agencies in meeting the State's climate goals. The research helps identify effective local strategies, assess policy impacts, address disparities, and improve implementation.

Housing-related research also helps CARB and other state partners in prioritizing policies that deliver cost-effective GHG reductions. This work draws on lessons from sustainable communities implemented worldwide. Likewise, many of CARB's research findings can be informative or transferable to other jurisdictions.

B. Sustainable Communities and Climate Mitigation

Sustainable communities are neighborhoods with safe, reliable, and affordable modes of transportation, equitable and affordable housing options, and access to quality employment, education, and other services. CARB's sustainable communities research informs the development of such communities across California by advancing the goals of SB 375 and encouraging the construction of environmentally sustainable and health-protective buildings.

Through the *Sustainable Communities and Climate Protection Program*, CARB encourages integrated regional planning that aligns transportation and land use to reduce vehicle miles traveled (VMT) and associated GHG emissions from passenger vehicles.

Past Research

Research highlights the importance of investing in communities that continue to face health and opportunity gaps while ensuring that efforts to build affordable housing in healthy, high-opportunity (HHO) neighborhoods do not worsen existing inequalities. The adoption of industrialized construction (IC) strategies, which can improve housing delivery across key performance metrics, has seen widespread success internationally, but remains limited in scale in the U.S. and California. A recently completed study[166] provided insight into the evolving landscape of IC adoption and its implications for future research and policy. Notably, the study informed a new grant program administered by the Strategic Growth Council, which leverages *California Climate Investments* to support the development of factories that will produce high-density, energy-efficient, and GHG-reducing housing using IC techniques.

Reducing VMT remains important for achieving California's climate goals. Case studies[167] examining changes in the built environment show that public investments in transit, biking, and pedestrian infrastructure can reduce driving and promote active transportation. However, better data on travel patterns is needed to more accurately assess these impacts. A recently completed project[168] combined survey data, micromobility travel data, and modeling to assess barriers to high-occupancy travel modes.

The COVID-19 pandemic also dramatically altered travel behavior, creating new challenges for transportation planners. A scenario analysis[169] explored policies that could help align post-pandemic travel trends with state climate and equity goals. Findings suggest that the pandemic may set the state back on its VMT reduction targets, which may require more ambitious, coordinated actions across state, local, regional, and federal levels.

Meanwhile, research into shared mobility programs in overburdened and low-income communities revealed persistent challenges in long-term financing.[170] Many of these programs rely on limited user fees and struggle to attract private investment due to high capital and operating costs. The project recommended integrating shared initiatives into larger transportation measures with dedicated funding.

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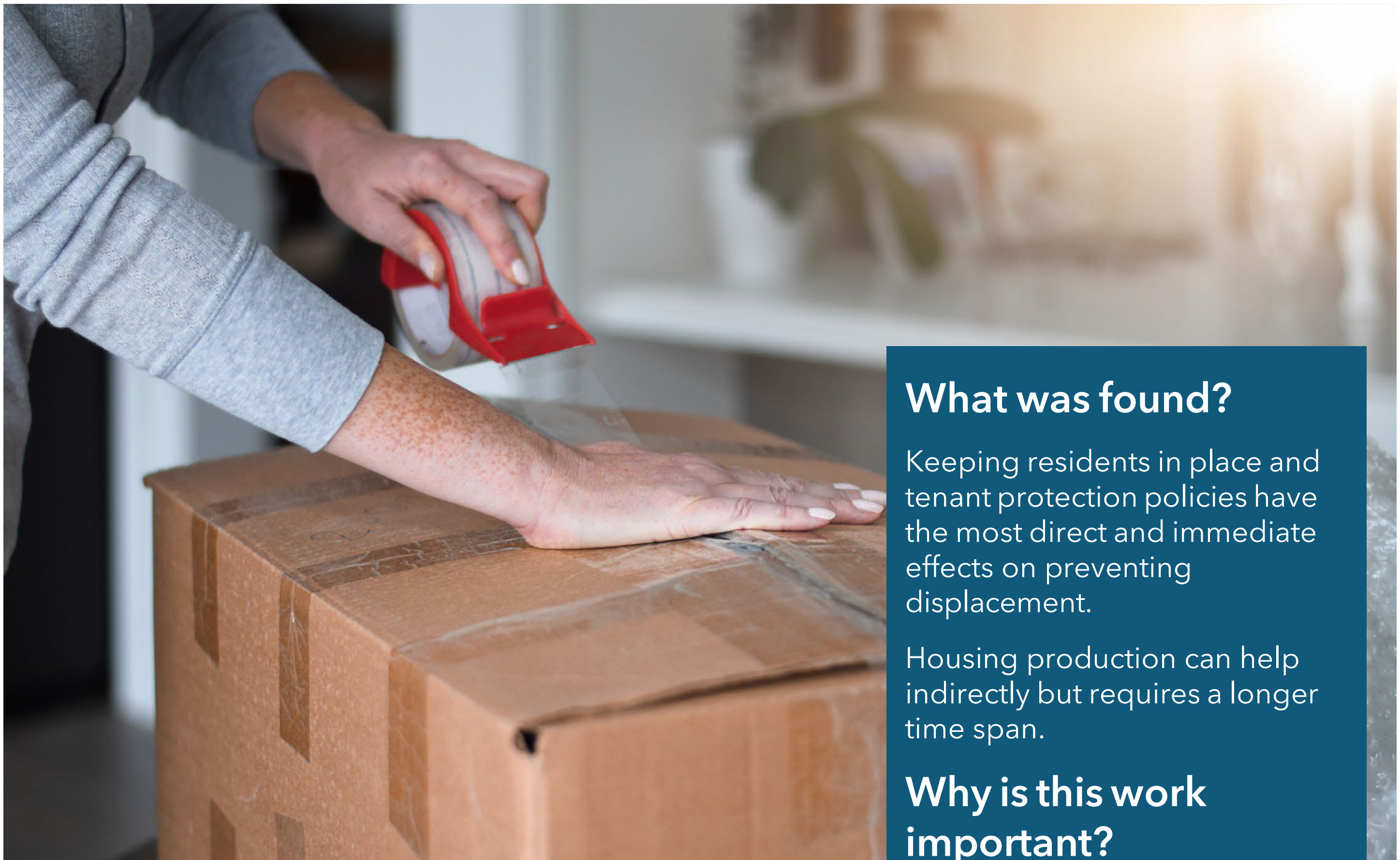
[166] CARB Contract 21STC020.
[167] CARB Contract *20RD006*.
[168] CARB Contract *19RD009*.
[169] CARB Contract *20STC008*.
[170] CARB Contract 21STC002.

Research Highlight: What Policies Can Prevent Housing Displacement?



Public investments in new neighborhood amenities, like public transit or parks, may have unintended consequences, such as increased rent or the displacement of existing residents.

Some state and local policies can help protect against this as California communities become more livable and sustainable.

CARB funded a **white paper** to better understand these anti-displacement policy options.

What was found?

Keeping residents in place and tenant protection policies have the most direct and immediate effects on preventing displacement.

Housing production can help indirectly but requires a longer time span.

Why is this work important?

Displacement can harm low-income tenants, immigrants, seniors, and other vulnerable groups.

This information can make sure public investments benefit **priority communities.**

How will results be used?

To inform anti-displacement strategies, program guidelines, and scoring criteria for competitive funding sources.

Current Research

Current research includes developing tools to measure accessibility and evaluating housing and transportation costs in overburdened communities.[171, 172] CARB is also working to streamline its SCS evaluation process by identifying practices to align regional and local plans with state goals.[173, 174] Another project incorporates community-based participatory research to ensure that those most impacted by past policies help shape solutions.[175]

CARB is also exploring a range of land-use strategies, such as transfer of development rights (TDR), and funding tools to support infill housing and reduce VMT, with a focus on affordability and best practices in disadvantaged communities.[176] Other projects are examining emerging mitigation approaches, such as VMT mitigation banks, telecommuting, and remote services.[177,178] The strategies have complex and evolving impacts on transportation, land use, and emissions, underscoring the need for further research and community engagement.

To support evidence-based decision-making, CARB is developing an in-house tool to evaluate VMT reduction strategies and related funding decisions.[179] This tool builds on existing modeling results from MPOs and incorporates expert input and external review to ensure transparency and rigor throughout its development. The research can also inform interagency collaboration under *Executive Order N-2-24*, which calls for a statewide mitigation framework to support infill development.[180]

To address gaps in current evaluation methods, CARB is also developing a new framework to evaluate how coordinated local transportation investments can improve accessibility, health, and opportunity outcomes across communities.[181] Another project is examining emerging modeling approaches to estimate induced VMT, which is a key factor in both project-specific and SCS evaluation processes.[182] Accurate estimates are essential for evaluating SCS success and informing policy decisions.

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[171] CARB Contract 22STC013.
[172] CARB Contract *22STC019*.
[173] CARB Contract 23STC015.
[174] CARB Contract *22STC010*.
[175] CARB Contract *22STC017*.
[176] CARB Contract 22STC020.
[177] CARB Contract 23STC013.
[178] CARB Contract 23STC017.
[179] CARB Contract 23STC016.
[180] CARB Contract *21STC011*.
[181] CARB Contract 23STC020.
[182] CARB Contract 23STC028.

Future Research Needs

Timely Drivers

Several upcoming milestones are expected to shape future research priorities in sustainable communities. In 2025, CARB is expected to propose metrics to evaluate the climate and environmental benefits of infill housing under *Executive Order N-2-24*, further connecting housing policy with climate goals and informing future research needs.

In 2026, CARB is required to update regional GHG emission reduction targets under SB 375, which guides land use and transportation planning to support the state's climate and air quality goals. These updates will inform future research priorities to support the development of new SCS. The *Regional Early Action Planning Grant Program (REAP 2.0)* also aims to accelerate infill housing development, reduce VMT, increase housing supply across all affordability levels, affirmatively further fair housing, and advance the implementation of regional and local plans. Evaluating REAP 2.0 outcomes will provide insights into effective strategies and help guide research needs.

CARB's sustainable community goals incorporate active transportation-related programs to support GHG reduction goals.[183] In 2013, legislation creating the *Active Transportation Program* (ATP) in the Department of Transportation (*Senate Bill 99, Stats. of 2013, Ch. 359* and *Assembly Bill 101, Stats. 2013, Ch. 354*). Programs like the ATP remain a key mechanism for achieving the goals of SB 375 and SB 341 (Statutes of 2009). CARB supports research to improve access, safety, and health outcomes, especially in overburdened communities.

These initiatives, along with the 2027 Scoping Plan, will continue to guide research on effective strategies to reduce VMT and meet statewide GHG reduction goals.

Future Research Priorities

- Are pro-housing measures increasing access and affordability while reducing VMT and transportation costs?
- Will these and similar measures help jurisdictions meet GHG reduction goals?

[183] *Active Transportation | California Air Resources Board*.

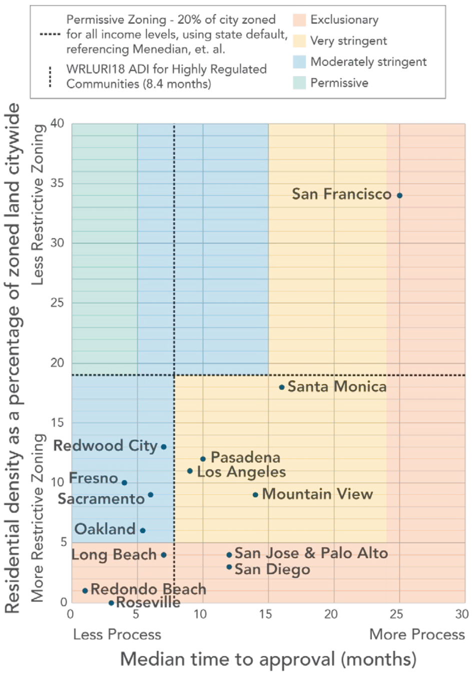
- What are the most promising opportunities for the State to support infrastructure investments that accelerate growth and development while advancing health, equity, climate, and environmental goals?
- What additional tools, data, or metrics could help expand housing opportunities and support more effective strategic decision-making across jurisdictions?
- How can the State reduce development costs and encourage the production of affordable housing and adaptive reuse projects, while continuing to make progress toward California’s climate goals?

- What are the economic, environmental, physical, and mental health benefits of public transit and communities designed to be walkable, bikeable, and accessible?
- What metrics and ground-truthing methods are most effective for evaluating strategies aimed at reducing dependence on personal vehicles and promoting sustainable mobility?

- What incentives and policies are effective in supporting the transition to walkable, bikeable, and transit-accessible communities?
- What accessible travel alternatives can be implemented to reduce reliance on personal vehicles, and how can those options be sustained over time?
- What strategies have been most successful in shifting travel behavior toward active transportation, complete streets, public transit, and micromobility?

- How can VMT reduction, congestion management, transportation equity, and generating revenue to sustain the transportation system be aligned and maximized through coordinated efforts across multiple agencies?
- What are the benefits and challenges of road pricing strategies, and how can these strategies be designed and implemented in California's urban, suburban, and rural areas to maximize benefits?

Research Highlight: Examining Building Entitlement in California



Entitlement is the process that property owners move through to get a building permit.

Local zoning and procedural rules in California's most expensive cities and counties limit the construction of dense and affordable housing.

What was found?

Zoning: Most of the more urbanized communities in California have very little land zoned for dense housing, and that limits how much housing may be built.

Process: Some cities have approval processes that take years. Cities that moved faster through approval processes also zoned comparatively little land for dense housing, so there were very few approvals across many years. The city that zoned the most land for dense housing also typically took many years to approve proposals to build dense housing, even when the proposals complied with all local rules.

Equity: In some places, zoning limits all new housing construction to neighborhoods with existing housing, requiring demolition and risking displacement to make way for new construction. In some communities, zoning limits all dense development to lower-income neighborhoods.

Why is this work important?

Lack of affordable new housing in cities can contribute to displacement and homelessness. More housing in dense, walkable areas with access to good transit will help meet state climate goals and reduce pollution. Some research suggests that state environmental review is a barrier to new housing in walkable neighborhoods.

This research explored how cities and counties write and apply their own law and state laws related to new housing development. The research focused on planning approvals (that come before construction permits) issued in 2014-2017 for housing that would produce five or more units. The research also examined how local governments apply state-required environmental review during the planning approval process.

How will results be used?

To inform housing development streamlining efforts, encourage more widespread use of streamlined review, and improve housing data collection.

C. Building Decarbonization and the Built Environment

Buildings are a major source of GHG and criteria pollutant emissions. To address this, CARB is advancing two main *building decarbonization* policies: the *Zero-Emission Space and Water Heater Standards* and reducing *embodied carbon*. The zero-emission standards for new space and water heaters align with the *2022 State Implementation Plan Strategy* by targeting reductions in both GHG and smog-forming oxides of nitrogen (NOx) emissions.

Embodied carbon, which refers to the lifecycle GHG emissions associated with the extraction, manufacturing, transportation, installation, maintenance, and disposal of goods, including building materials, can account for up to 50% of building-related GHG emissions. Under *AB 2446* and *AB 43*, CARB is developing a framework and strategy to reduce embodied carbon emissions by 40% by 2035.[184, 185, 186]

Current Research

CARB is funding multiple projects that explore strategies to equitably decarbonize buildings. One study[187] examines the disparities in electrification costs and impacts for priority populations living and working in existing buildings. The project leverages permit data, records, and surveys of renters and multifamily property owners regarding building decarbonization decisions. The results will inform efforts to better align incentives, regulations, and policies to support equitable building decarbonization. Another project[188] uses a participatory action research model to strengthen community capacity for equitable housing decarbonization.

CARB is also studying energy use in priority communities to inform inclusive policy development, particularly in areas that rely on propane or wood for heating.[189] In the nonresidential sector, which accounts for about one-third of building-related GHG emissions, CARB is funding research[190] on retrofit needs for installing zero-emission equipment and appliances across various building types.

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184 *Carbon Leadership Forum. 2022. "Embodied Carbon Policy Strategies: Presentation."* Carbon Leadership Forum. 2022. "Embodied Carbon Policy Strategies: Presentation."

185 *Esau, R., M. Jungclaus, V. Olgyay, and A. Rempher. 2021. "Reducing Embodied Carbon in Buildings: Low-Cost, High-Value Opportunities." RMI.*

186 *California Energy Commission. 2022. "Final 2021 Integrated Energy Policy Report."* California Energy Commission. 2022. "Final 2021 Integrated Energy Policy Report."

187 CARB Contract 21SCT023.

188 CARB Contract *22STC018*.

189 CARB Contract 23STC009.

190 CARB Contract 23STC006.

Two projects[191, 192] are supporting the goals of AB 2446 and AB 43 by analyzing embodied carbon in building materials. The first project evaluates data sources, technologies, and global policies to improve understanding of the sources and scale of embodied carbon emissions associated with building materials. The second project examines the feasibility, costs, and policy strategies for reducing embodied carbon in building materials.

Future Research Needs

Timely Drivers

Reducing GHG emissions from buildings is important to achieving California's climate goals, including the SB 32 target of reducing statewide GHG emissions to 40% below 1990 levels by 2030. Ongoing and future research will also support CARB's effort to meet embodied carbon emission reduction goals established under AB 2446. As CARB advances building decarbonization policies, it will work closely with communities to address disparities and consider impacts on housing costs and affordability. Additional research, particularly community-engaged studies, has the potential to develop feasible, cost-effective, and health-protective standards that help meet the state's GHG reduction goals.

[191] CARB Contract *22STC014*.
[192] CARB Contract 23STC019.

Future Research Priorities

- How can building decarbonization efforts be designed to ensure a just and equitable transition?
- What policies, programs, and protections would help overburdened communities decarbonize homes and businesses, with particular attention to affordability, accessibility, community priorities, renters, and workforce development?
- What strategies or incentives can encourage landlords to transition to zero-emission appliances, such as those for heating, water, clothes drying, and cooking, without increasing rents or displacing tenants?

- How does the use of low-carbon building materials affect overall construction and housing costs, and what are the trade-offs or co-benefits?
- What strategies can effectively reduce GHG and air pollutant emissions from construction sites to improve air quality and support climate goals??

- How effective are different building decarbonization strategies in addressing ambient and indoor air quality disparities and associated health outcomes?
- What are the health, air quality (both ambient and indoor), and economic impacts of decarbonizing residential, public, and commercial buildings?
- Are there cumulative emissions disparities between single-family and multi-family units, and how do these differences affect health and environmental equity?

Conclusion and Next Steps

This 5-Year Plan was developed through extensive coordination and engagement with a broad range of partners and collaborators, ensuring that the final research priorities are aligned with policy needs, public concerns, and scientific knowledge gaps. These priorities are currently expected to guide the selection of annual research projects from 2025 through 2030, resulting in focused and forward-looking studies.

CARB will also coordinate with other agencies, particularly those with greater funding capacity, to address research needs where CARB's budget may be limited. The Research Program will continue to engage with the public, including with overburdened communities, to identify emerging issues that can be addressed through research.

Based on the current plan, CARB will initiate its annual research planning process in the first half of the calendar year by distributing a public survey to rank the top priorities in this Five-Year Plan. This will be followed by a public meeting to discuss these priorities in greater detail. Feedback collected will help shape the final list of research concepts, some of which may undergo additional community-centered engagement. Notifications about further engagement opportunities will be shared each year.

Centuries of scientific advancements and decades of data collection have shaped our understanding of the harmful impacts of air pollution on public health, the local and global environment, and health disparities across communities. Through its research planning process, CARB will continue to rely on robust science to identify existing and emerging public health and environmental threats and pursue data-driven policy and technology solutions.

To stay informed about CARB's research planning and activities, visit the *CARB Research Planning website* and sign up for the *CARB listserv* by selecting the "Research Activities" option.