Development of Fine-Grained Spatial Resolution for an Integrated Health Impacts Assessment Tool for the Sacramento Region

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A Research Report from the National Center for Sustainable Transportation

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16. Abstract
Understanding the public health impacts of transportation plans can inform decision making and project prioritization. Because each plan and regional context is different, there is a need for site-specific methods to assess the extent and distribution of health impacts of changes to a region's transportation system. To fill this need, researchers have developed the Integrated Transport and Health Impact Model (ITHIM), which predicts the public health impacts of transportation and land use scenarios from expected changes in air quality, traffic safety, and physical activity. However, current transportation health impact assessment models (including ITHIM) operate at coarse geographic scales (e.g. region or county) to quantify health changes. This research builds on previous work using ITHIM to generate demographically explicit health outcomes to provide neighborhood-level estimates of public health changes predicted from transportation plan scenarios in Sacramento, California. We assess the impacts of regional transportation plan scenarios on public health via changes in traffic injury and physical activity. Zip-code level results are mapped using a customizable web interface. Illustrative results indicate that the adopted regional transportation plan will lead to improved health outcomes, largely driven by the benefits of increased physical activity. However, these estimates vary widely across the region, with some communities expected to experience adverse impacts and others obtaining higher levels of benefit. We note that some of the variation may be the result of modeling noise, and we identify promising avenues for improving the robustness of estimates at small spatial scales. Disaggregation is important from sustainability and equity perspectives to determine the locations where and populations for whom the physical activity benefits of non-motorized transportation are outweighed by increased exposure to the risk of air pollution and injury or death. Providing an accessible, web-based tool to illustrate the effects of transportation plans and in communities across a region has the potential to elevate health and equity considerations in transportation decision making. The methods developed in this study can be refined and improved and applied elsewhere by modifying the source code, which is publicly available.

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Disclaimer

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Judy Robinson at Sacramento County provided valuable insight into potential uses for ITHIM-Sacramento and helped the project team connect with other local stakeholders. We thank Neil Maizlish for the data collection in the original version of ITHIM-Sacramento. We also thank Bruce Griesenbeck and Yanmei Ou of SACOG for providing access to SACSIM15 outputs. We would like to acknowledge Jason Vargo and Samuel Younkin at University of Wisconsin – Madison Health Institute for assistance in the R-based ITHIM development.

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EXECUTIVE SUMMARY

Plans crafted by metropolitan planning organizations (MPOs) lay out how billions of dollars in transportation investments will be made over a 20 to 30-year time horizon. Federal transportation authorizations require MPOs to identify and track key indicators of system performance (e.g., collision rates, emissions, and congestion) to ensure that they are stewarding public funds wisely to meet specific goals related to safety, environmental performance, and congestion mitigation, among other areas.

At the same time, there is a growing desire among transportation planning agencies to develop transportation and land use plans that shift travel behavior away from driving and towards more active travel modes. Research has shown that living in areas where walking and bicycling are convenient leads to greater use of those modes, which can lead to improved health outcomes due to increases in physical activity. But increasing non-motorized travel can also increase active travelers' risk of traffic injury and exposure to air pollution. Analytical tools that assess the tradeoffs between transportation plan alternatives are needed to inform public debate and ensure that gains in some health outcomes are not being undermined by losses elsewhere. To fill this need, researchers have developed the Integrated Transport and Health Impact Model (ITHIM), which predicts the public health impacts of transportation and land use scenarios from expected changes in air quality, traffic safety, and physical activity (*1*, *2*).

However, current transportation health impact assessment models (including ITHIM) that operate at coarse geographic scales (e.g., region or county) to quantify health changes are unable to illuminate questions about which sub-populations will benefit from targeted infrastructure investments that promote increases in active travel.

The aim of this project is to build on previous work using a Sacramento-region calibration of ITHIM to generate demographically explicit health outcomes (*3*) to provide neighborhood-level estimates of public health changes predicted from transportation plan scenarios. The project is demonstrated by investigating the spatial distribution of public health impacts resulting from a regional transportation plan in the six-county Sacramento Area Council of Governments (SACOG) region. This report summarizes findings related to our two key goals:

1. **Employ a refined version of the Integrated Transportation Health Impacts Model (ITHIM) to quantify health impacts resulting from the 2016 SACOG Metropolitan Transportation Plan/Sustainable Communities Strategy.** We adapt ITHIM to produce estimated changes in death and disease burden at a fine-grained spatial resolution. Results are presented as total health burden (e.g., total change in deaths, to indicate the magnitude of impacts), as well as standardized by age and population (e.g., risk per

person using a typical age profile), to facilitate comparisons of risks faced by people living in different geographic areas.

2. **Report on the development of a user-friendly web interface for summarizing ITHIM results**. In response to the requests of various health and sustainability stakeholders in the SACOG region, we created a web version of our tool that can be used to visualize existing model results. This web interface allows a user to tailor the results shown by scenario.

We caution that the results shown here may reflect uncertainties in estimates derived at small spatial scales and so are included for illustrative purposes only. We therefore add a third objective to this work and summarize these results:

3. **Identify promising strategies for improving modeled results.** The development of the spatially refined model shown here has highlighted the difficulty of modeling accurate estimates at small spatial scales. We identify a number of promising refinements that have the potential to improve the reliability of these estimates.

Our results demonstrate the promise of analyzing and representing the public health impacts of transportation plans in a user-friendly way for planners, policy makers, and advocates. The methodology and promising avenues for improvement presented in this project can provide guidance for those working on active transportation, public health, and regional equity in other locations across the United States.

Introduction

An important product of the regional transportation planning process is a long-range plan and a short-term spending program. Plans crafted by Metropolitan Planning Organizations (MPOs) lay out how billions of dollars in transportation investments will be made over the subsequent 20 to 30 years. They identify the challenges that a region faces and describe how the plan will help to alleviate those challenges via transportation infrastructure investments and policy strategies. Historically, a single preferred plan was identified through a process of regional consensus-seeking and put forward to the residents of a region before being adopted by an MPO's board. That practice began to change in California, first in the Sacramento region, and then elsewhere, as agencies and the public increasingly sought to understand how alternative transportation and land use scenarios would affect the performance of the entire transportation system (*4*, *5*). This work was prompted by state policies such as Senate Bill 375, California's Sustainable Communities and Climate Protection Act of 2008.

The idea of performance assessment has since become embodied in federal transportation policy (*6*). The Moving Ahead for Progress in the 21st Century (MAP-21) Act and its follow-up transportation authorization, the Fixing America's Surface Transportation (FAST) Act, both require MPOs to conduct performance-based transportation planning. In other words, they must identify and track key indicators of system performance (e.g., collision rates, emissions, congestion) to ensure that they are stewarding public funds wisely to meet specific goals related to safety, environmental performance, and congestion mitigation, among other areas.

One topic that is increasingly gaining attention is the public health impacts of transportation planning and programming activities (*7*–*11*). In the U.S., these impacts first became apparent with early air pollution crises during the 1950s in Los Angeles. Since that time, automobiles' contribution to air pollution, and the importance of air quality issues in general in the U.S., has been declining in importance due to improvements in automotive and fuel technology (e.g., *12*). Risks of death and injury from vehicle collisions are another area that have historically been important but have been declining in importance over time as safety technology, seatbelt laws, and driver behavior undergo substantial changes (*13*). Automobile dependence looms large in both types of impacts, but reliance on the car also influences levels of physical activity. Over 8% of deaths in the U.S. can be attributed to a lack of physical activity (*14*). Walking and biking can be considered moderate to vigorous activity and can contribute to meeting current physical activity guidelines (*15*). Research has shown that living in areas where walking and bicycling are convenient leads to greater use of those modes (*16*). But, increasing non-motorized travel can also increase injury risk and exposure to air pollution (*17*).

Analytical tools that assess the tradeoffs between transportation plan alternatives are needed to inform public debate and ensure that gains in some health outcomes are not being undermined by losses elsewhere. The need for such tools is also motivated by an increasing desire among transportation planning agencies to develop transportation and land use plans that shift travel behavior away from driving and towards more active modes (*18*). To fill this need, researchers have developed the Integrated Transport and Health Impact Model (ITHIM), which predicts the public health impacts of transportation and land use scenarios from expected changes in air quality, traffic safety, and physical activity (*1*, *2*).

Previously conducted health impact assessments (including those that use ITHIM) have generally found that although there are both benefits and risks expected when rates of active travel increase, benefits outweigh risks in most cases (*17*, *19*). However, current transportation health impact assessment models (including ITHIM) that operate at coarse geographic scales (e.g., region or county) to quantify health changes are unable to characterize the health effects of active travel investments in smaller geographic areas. The magnitude of health benefits and risks associated with transportation investments can vary greatly across space because changes in physical activity, air pollution exposure, safety risks, and demographics all vary spatially with a particular investment scenario. Understanding health outcomes at the sub-region or sub-county scale can better inform decision makers about who benefits from investments and also which areas might be in need of targeting interventions to increase physical benefits or reduce safety or air quality risks.

The work presented here enhances earlier versions of ITHIM-Sacramento by developing a framework for providing *highly spatially disaggregate* estimates of the public health changes expected to result from plan implementation. The disaggregate results presented here demonstrate the challenge inherent in understanding these effects at small spatial scales. We also discuss future directions for improving these estimates.

Disaggregating these results has the potential to increase the utility of the existing ITHIM-Sacramento tool for understanding spatial variations in public health changes. Disaggregation is especially important from both transportation sustainability and transportation equity perspectives to determine the *locations where* the physical activity benefits of non-motorized transportation are outweighed by increased exposure to the risk of air pollution and injury or death, as well as locations that merit targeting investment to increase benefits or reduce risks.

The aim of this work is to investigate the spatial distribution of public health impacts resulting from a regional transportation plan in the six-county Sacramento Area Council of Governments (SACOG) region. This report summarizes findings related to our two key goals:

1. **Employ a refined version of the Integrated Transportation Health Impacts Model (ITHIM) to quantify health impacts resulting from the 2016 SACOG Metropolitan Transportation Plan/Sustainable Communities Strategy.** We adapt ITHIM to produce results at a fine-grained spatial resolution.
2. **Report on the development of a user-friendly web interface for summarizing ITHIM results**. In response to the requests of various health and sustainability stakeholders in the SACOG Region, we created a web version of our tool that can be used to visualize existing model results.

We caution that the results shown here may reflect uncertainties in estimates derived at small spatial scales and so are included for illustrative purposes only. We therefore add a third objective to this work and summarize these results:

3. **Identify promising strategies for improving modeled results.** The development of the spatially refined model shown here has highlighted the difficulty of modeling accurate estimates at small spatial scales. We identify a number of promising refinements that have the potential to improve the reliability of these estimates.

Our results demonstrate the promise of summarizing the public health impacts of transportation plans and can provide guidance to those working in other locations across the U.S.

Sacramento Application

Overview

The primary purpose of this work is to enhance previous versions of the Sacramento-region implementation of ITHIM to facilitate spatially detailed analyses of transportation plans. We synthesize data from a range of sources. The ITHIM-Sacramento spatial analysis tool estimates health outcomes from changes in physical activity and traffic injury in the six SACOG counties (El Dorado, Placer, Sacramento, Sutter, Yolo, and Yuba), disaggregating results by zip code. We illustrate the promise of the ITHIM-Sacramento spatial analysis tool by evaluating expected health outcomes due to changes in physical activity and traffic injury that are expected under SACOG's 2016 Metropolitan Transportation Plan / Sustainable Communities Strategy (MTP/SCS) scenarios and the adopted plan.

Our results include some unexpected findings which may be caused by the empirical challenges raised when disaggregating the analysis to small spatial scales. We use this modeling exercise to 1) develop a framework for evaluating ITHIM at small spatial scales; 2) illustrate the potential of understanding spatially detailed health outcomes to inform regional planning efforts; and 3) identify promising directions for improving the accuracy of disaggregate analyses of the health effects of transportation plans.

Methods and Data

The fundamental methodological approach employed by ITHIM is known as comparative risk assessment (CRA). In the ITHIM CRA, the relationships between changes in travel behavior and expected health outcomes are obtained from a robust set of scientific research studies. These general relationships are applied to region- and scenario-specific population and travel data to estimate health outcomes that are expected to occur under different transportation plans. Data for the Sacramento ITHIM implementation are compiled from a number of sources describing demographics, transportation behavior, physical activity, traffic injury, and health. Below we provide an overview of the modeling methods. A more detailed discussion of ITHIM-Sacramento methods and results can be found in the "Modeling Health Equity in Active Transportation Planning" working paper posted at https://doi.org/10.5281/zenodo.3424327. These estimation methods are similar except that the disaggregation is spatial rather than demographic, as described below.

Scope

To demonstrate the tool, we evaluate health outcomes of the adopted 2016 MTP/SCS for three future years (2020, 2027, and 2036) and evaluate outcomes of three alternative scenarios (S1, S2, and S3) in 2036. The three scenarios vary in terms of the housing and transportation provisions planned (Table 1). S2 is the "preferred scenario" and is similar to the adopted 2016 MTP/SCS except that the adopted plan has more transit service and slightly less new or expanded roads, and funnels more growth into established communities. S1 plans for less growth into center and corridor communities and has a greater emphasis on auto travel than

S2. S3 plans for more growth in center and corridor communities and has a greater emphasis on multimodal travel than S2. All scenario and future year results are presented as a change in outcome relative to 2012, which is modeled as the baseline year.

Table 1. Description of the 2016 MTP/SCS Scenarios. (*20*)

	S1	**S2**	**S3**	**Adopted 2016 plan**
Transportation investments				
New or expanded roads (lane miles, % increase from 2012)	**31%**	27%	23%	24%
Transit service (vehicle service hours, % increase from 2012)	54%	109%	**143%**	122%
Bike and pedestrian improvements ($ in billions)	$2.8	$2.8	**$3.0**	$2.8
Land use planning				
Share of growth in "Center and Corridor Communities" (percent of homes)	20%	31%	**36%**	30%
Share of growth in "Established Communities" (percent of homes)	**29%**	25%	27%	28%
Share of growth in "Developing Communities" (percent of homes)	**47%**	42%	36%	40%
Newly developed land (acres of development, % increase from 2012)	**11%**	7%	5%	7%
Transportation outcomes				
Vehicle miles traveled (per person per day)	**17.6**	17.2	16.0	17.0
Mode share for transit, walking, bicycling (percent of all person-trips)	12%	12%	**14%**	13%

Physical Activity

In the physical activity module, we combine baseline health data, baseline non-transport physical activity data, and baseline and scenario transport-related physical activity to estimate the health benefits of increases in walking and biking that are expected to occur under each plan scenario.

Baseline health data include the overall disease burden for the U.S. (from the 2010 Global Burden of Disease, or GBD, database). We use disability-adjusted life years (DALYs) as a measure of disease burden. DALYs are a measure of disease burden that considers both life years lost due to premature mortality and the reduction in quality of life caused by life years spent living with illness-related disability. Baseline health data also include all-cause mortality rates for the Sacramento region (from 2008-2010 California Department of Public Health, or

CDPH, vital statistics). Baseline non-transport physical activity data are from the 2005 California Health Interview Survey. These baseline health and non-transport physical activity data are obtained at the regional level and are scaled to the zip code level based on the age-gender population distribution in each zip code, as described below.

Baseline and scenario-specific transport related physical activity are estimated from outputs of SACSIM15, SACOG's activity-based travel demand model. These estimates are available at the sub-regional level and are converted to the zip code level, as described below.

We combine baseline health and non-transport physical activity data with changes in transport-related physical activity to estimate expected changes in deaths and DALYs due to changes in active travel using health relationships established in scientific literature.

Traffic Injury

In the injury module, we combine baseline transport injuries and collision rates with baseline and scenario travel distances by mode to estimate the change in collision risks due to changes in walking, biking, and driving. U.S. baseline transport injury rates are from the 2010 GBD database. Sacramento region baseline 2006–2016 collision rates are from the Statewide Integrated Traffic Records System (SWITRS) and the Transportation Injury Mapping System (TIMS). These baseline transport injury and collision rates are obtained at the regional level and are scaled to the zip code level based on miles traveled using each mode at the zip code level, as described below.

Baseline and scenario travel distances by mode are estimated from outputs of SACSIM15. These estimates are available at the sub-regional level and are converted to the zip code level, as described below.

We combine transport injury and collision rates with changes in travel distances by mode to estimate expected changes in deaths and DALYs due to changes in active travel using health relationships established in scientific literature.

Disaggregating Estimates by Zip Code

To conduct the fine-grained / localized spatial analysis, we require data for each zip code. We first obtain U.S. 2010 Census population data for age and gender at the zip code tabulation area (ZCTA) for the 151 ZCTAs that are completely within the SACOG region.[1]

Baseline mortality rates are estimated at the ZCTA level by multiplying the age-gender population distribution of each ZCTA by Sacramento region-wide rates (as deaths per capita in

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[1] Note that ZCTAs approximate zip code locations but are not exactly the same.

each age-sex category), where region-wide rates are estimated from the CDPH 2008 to 2010 vital statistics.[2]

Scenario-specific transport-related physical activity for a synthetic population is available at the traffic analysis zone (TAZ) level from SACSIM15 outputs. ZCTAs are larger than TAZs, and most TAZs fall completely within a single ZCTA. Where TAZs straddle more than one ZCTA, residents are allocated to each ZCTA in proportion to the area of overlap.

Non-transport physical activity is estimated at the ZCTA level by multiplying the age-gender population distribution of each ZCTA by Sacramento region-wide activity (as non-transport physical activity in each age-sex category), where region-wide activity is estimated from the 2005 California Health Interview Survey.

Baseline injury data from the 2006–2016 SWITRS data are stratified by striking and victim modes, severity, and road type. Region-wide injury rates[3] for each combination are applied at the zip code level in proportion to miles traveled for each mode, where the miles traveled for each mode is obtained at the TAZ level from SACSIM15 outputs and applied to the zip code level using the area-weighting method described above for transport-related physical activity.[4]

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[2] Although we have zip code level mortality data, when disaggregating by age and gender, which are important factors related to mortality risks, we encounter a small numbers limitation (where observed mortality data are "noisy" because the population examined is very small). We attempted to estimate zip code level mortality risks at the ZCTA level using statistical regression accounting for a number of socioeconomic factors but were unable to resolve the model. A request for additional mortality data (spatially detailed and for a longer time period) from CDPH, which might be used to improve the statistical regression, could not be fulfilled on this project timeline. Future work might explore improving the baseline mortality estimates using regression and/or additional mortality data.

[3] Although injury data are available at specific locations, when they are summarized at the ZCTA level, we observe a small numbers limitation: injury rates equal zero in many areas although we infer that there is a non-zero risk. For example, areas with a risk of 0.05 injuries per year for some combination of striking mode, victim mode, severity, and road type would be expected to have observations of zero in most years.

[4] Because the baseline injury is related to both striking mode VMT and victim mode VMT, we consider both ratios in the scaling process as follows:

$$Injury_{ZCTA} = Injury_{RegionWide} \times \left[\left(\frac{VMT_{striking,ZCTA}}{VMT_{striking,RegionWide}} \right)^m \times \left(\frac{VMT_{victim,ZCTA}}{VMT_{victim,RegionWide}} \right)^n \right]$$

where m and n are set equal to 0.5 representing a safety-in-numbers relationship. This formulation may be imperfect as it applies the safety-in-numbers concept to a subset of the region (vs. applying it to different scenarios). In this study this formula approximately conserves the total number of fatalities in the region (with a difference of less than 2% when aggregating all zip codes and comparing to region-wide totals). Improvements to the spatial allocation of injury rates could be further explored in future work.

Results and Discussion

Below we present estimated health outcomes for each scenario evaluated. We evaluated health outcomes of the adopted 2016 MTP/SCS for three future years (2020, 2027, and 2036) and for the three alternative scenarios (S1, S2, and S3) in 2036. All results were evaluated as a change in outcome relative to 2012, which is modeled as the baseline year. Health outcomes were evaluated in two ways: 1) as the total, or absolute, number of deaths and DALYs; and 2) standardized by the age-gender distribution and magnitude of the population size. Total death and DALY values provide insight into the magnitude of the impacts in a particular geographic area. Death and DALY estimates that are standardized by the age-gender distribution and population size are essentially risks that account for differences in a population's size and age-gender distribution to facilitate comparisons of the risks faced by individuals in different geographic areas. These standardized values show the risk of death or DALYs assuming identical population sizes and age-gender distributions.

We start by presenting regionally aggregate results for changes in travel behavior and the associated change in absolute deaths under the adopted plan (FiguresFigure 1,Figure 2) and the three plan scenarios in 2036 (Figures Figure 3,Figure 4) under each scenario. These results were modeled at the zip code level as described above and then aggregated to the regional level to present an overview of results.

The adopted plan initially exhibits an increase in bike and motor vehicle travel, with vehicle travel reductions and growing gains in bike and pedestrian travel in later years (Figure 1). The physical activity benefits of the adopted plan are greatest in 2020, likely resulting from increases in bike travel from 2012 to 2020 (Figure 2). Injury risks initially grow, likely as a result of greater motor vehicle and bike travel, and then shrink, likely as a result of less motor vehicle travel. It is noteworthy that the magnitude of injury risks in 2020 exceeds physical activity benefits; this is contrary to what is typically found using ITHIM and other methods (*19*) and may point to model noise when using disaggregate analysis. Results for DALYs are similarly compromised by the methodological limitations (not shown).

As expected, Scenario 1 results in the most vehicle travel in 2036, while Scenario 3 results in the most non-auto travel and Scenario 2 falls in between (Figure 3). Looking at the reduction in deaths, the large increase in deaths (shown as a negative value) due to physical activity under Scenario 1 appears is driven by an estimated increase in deaths of 53 in one zip code, which can be traced to a very large increase in walking by elderly female residents.[5] This result seems to point to the difficulties inherent in the health modeling methods used here as well as

[5] A large change in physical activity for this group results in very large changes in deaths and DALYs because this group has a very high baseline mortality rate. The large change in physical activity reflected in the data (over 2 hours per person per day in Scenario 1) may be due to a computational error or due to noise in the travel model itself but seems unlikely to reflect actual travel outcomes.

limitations of the travel demand model at small spatial scales. Results for DALYs are similar (not shown).

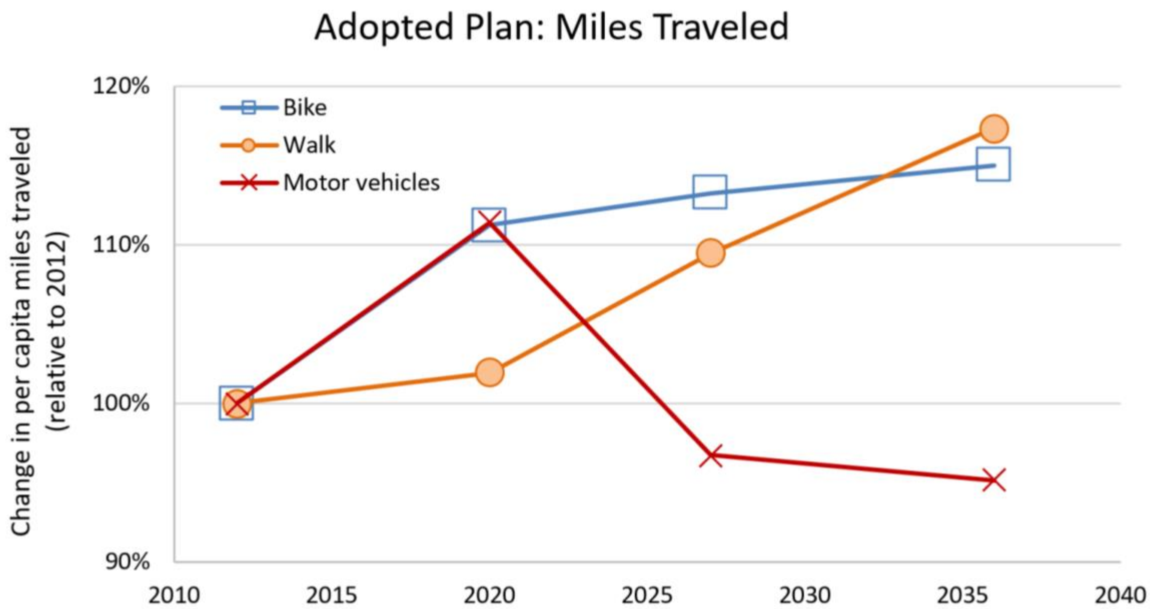

Figure 1. Miles traveled by mode under the adopted plan.

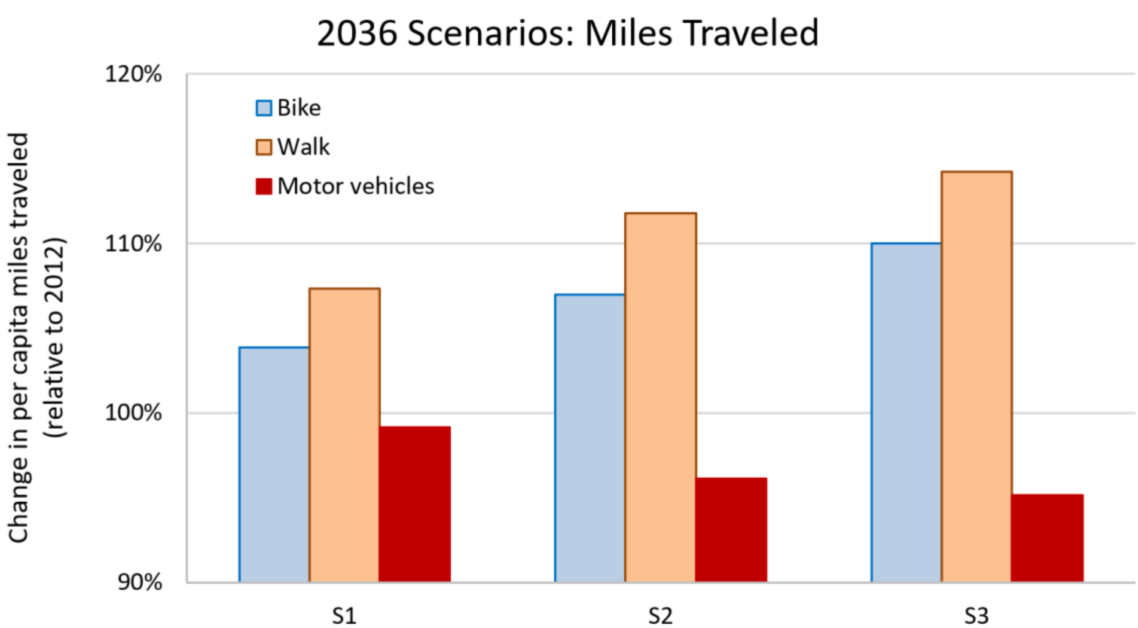

Figure 2. Miles traveled by mode under the 2036 scenarios.

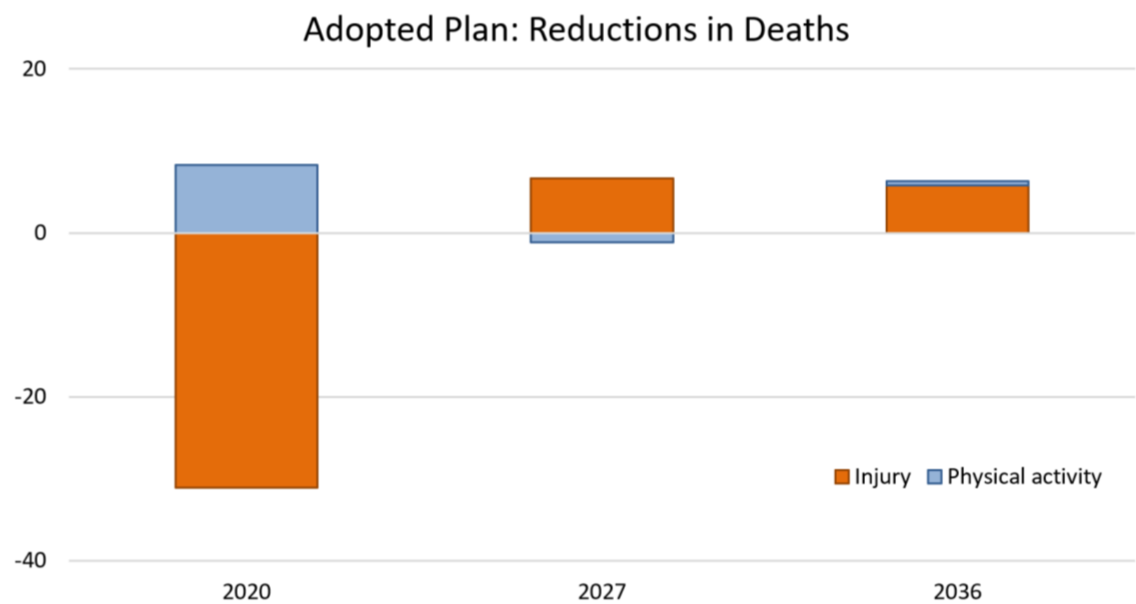

Figure 3. Reductions in death under the adopted plan. Positive values represent benefits and negative values represent adverse effects.

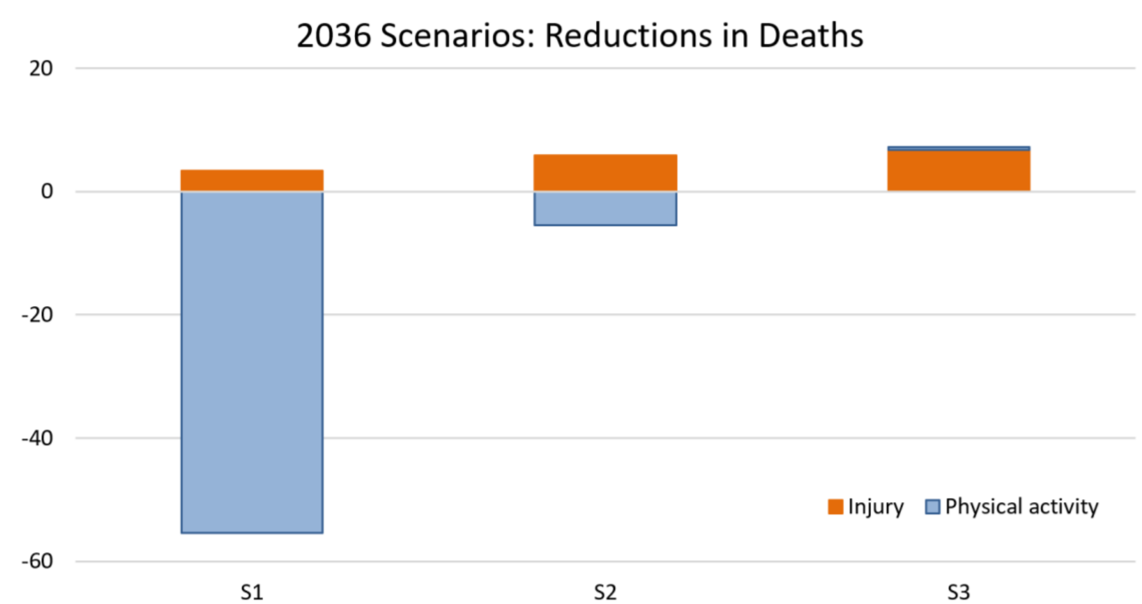

Figure 4. Reductions in death in 2036 under three scenarios. Positive values represent benefits and negative values represent adverse effects.

As noted above, the modeling results appear to show some noise that results from the disaggregation of results. As a result, in this section we present a subset of results for illustrative purposes only. We note that the results shown may not reflect actual plan outcomes but can be used to visualize the potential of disaggregate health estimates.

Figures Figure 5, Figure 6,andFigure 7 show the reductions in death for zip codes across the region for changes in physical activity, traffic injury, and both combined, respectively. Note that positive (green) values represent health benefits while negative (red) values indicate health burdens. These maps demonstrate the variation in total death reductions (from physical activity, traffic injury, and combined) in zip codes across the region; variation is driven by spatial differences in population and changes in travel behavior relative to the 2012 baseline. The larger health burdens of traffic injuries under the adopted plan in 2020 (Figure 6) are explained by greater VMT in that year, where more auto travel increases the expected fatalities. Detailed results for total deaths can also be viewed at https://aakarner.shinyapps.io/ITHIM-Sacramento-Spatial/. This web interface allows users to view interactive maps of estimated total deaths, while tailoring the results by scenario.

FiguresFigure 8,Figure 9, andFigure 10 show the expected reductions in disability-adjusted life years (DALYs) for zip codes across the region for changes in physical activity, traffic injury, and both combined, respectively. As above, positive (green) values represent health benefits while negative (red) values indicate health burdens. These maps reflect similar variation as are shown in the total death Figures (Figure 5, Figure 6,andFigure 7).

Figures Figure 11,Figure 12, andFigure 13 show the expected reductions in death risks (presented as age-standardized deaths per 100,000 people) for zip codes across the region for changes in physical activity, traffic injury, and both combined, respectively. As above, positive (green) values represent health benefits while negative (red) values indicate health burdens. Figures Figure 14, Figure 15, andFigure 16 show the expected reductions in DALYs risks (presented as age-standardized DALYs per 100,000 people) for zip codes across the region for changes in physical activity, traffic injury, and both combined, respectively. As above, positive (green) values represent health benefits while negative (red) values indicate health burdens.

The results standardized by age and population shown in Figures Figure 11 throughFigure 16 are an indication of the changes in the risk of death faced by the average resident of each community whereas the total results shown in Figures Figure 5 through Figure 10 reflect the changes in impact to each community as a whole (which depends on the average risk to each resident and the total population and its distribution by age and gender). For example, suppose that community A's residents are all in their twenties and community B's residents are all in their sixties and both communities have the same baseline travel behavior and then experience identical changes in travel behavior. The change in total deaths (corresponding to community-level impacts) will be greater in community B while the change in standardized deaths (corresponding to individual-level risks) will be the same in both communities. Similarly, if community C has a population of 10 and community D has a population of 100,000 (and they have the same baseline and change in travel behavior) then the change in total deaths will be greater in community D while the change in deaths standardized by age and population will be the same in both communities. In other words, the community-level impacts will be greater in community D although the change in individual-level risks will be the same in both communities. Thus, standardized estimates facilitate comparisons of the change in risk across communities holding their population size and age-gender distributions constant.

As with the total death reductions and DALYs, the death and DALY *risk* reductions demonstrate variation in zip codes across the region, although the specific patterns of variation differ. This variation is attributable to different changes in travel behavior relative to the 2012 baseline. Traffic injuries again stand out as causing an increased burden under the adopted plan in 2020.

Note that data for one zip code (95966 in Oroville) is excluded from all maps because the Scenario 1 physical activity health burdens are outlying and skew the map legend enough to obscure the rest of the results. This zip code exhibits very large increases in total deaths and DALYs in Scenario 1, as noted above.

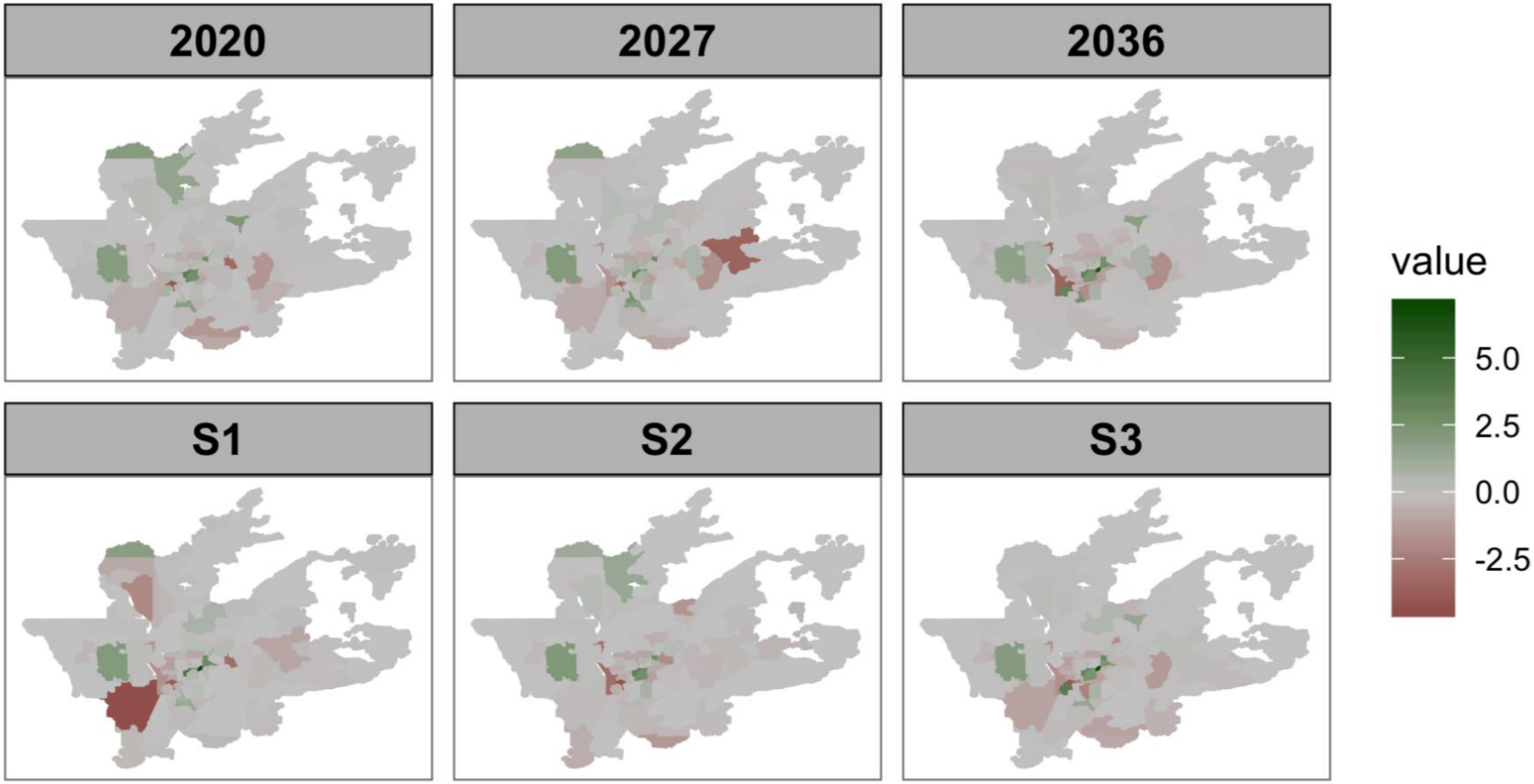

Figure 5. Total expected reduction in deaths from changes in physical activity (results shown are for illustrative purposes only). The top row shows the adopted plan in 2020, 2027, and 2036. The bottom row shows Scenarios 1, 2, and 3 in 2036. Positive (green) values indicate health benefits while negative (red) values indicate worsening health outcomes.

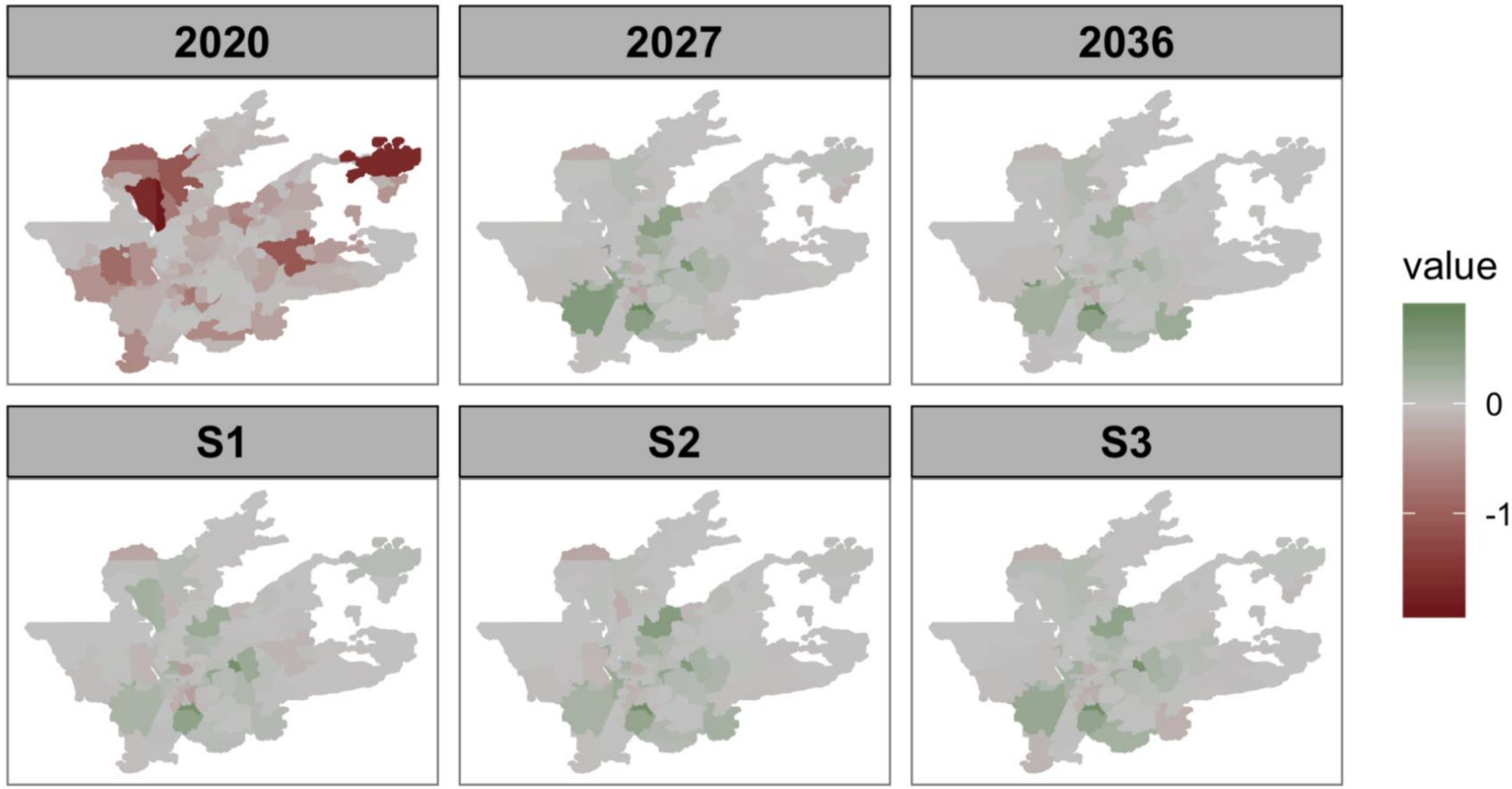

Figure 6. Total expected reduction in deaths from traffic injury (results shown are for illustrative purposes only). The top row shows the adopted plan in 2020, 2027, and 2036. The bottom row shows Scenarios 1, 2, and 3 in 2036. Positive (green) values indicate health benefits while negative (red) values indicate worsening health outcomes.

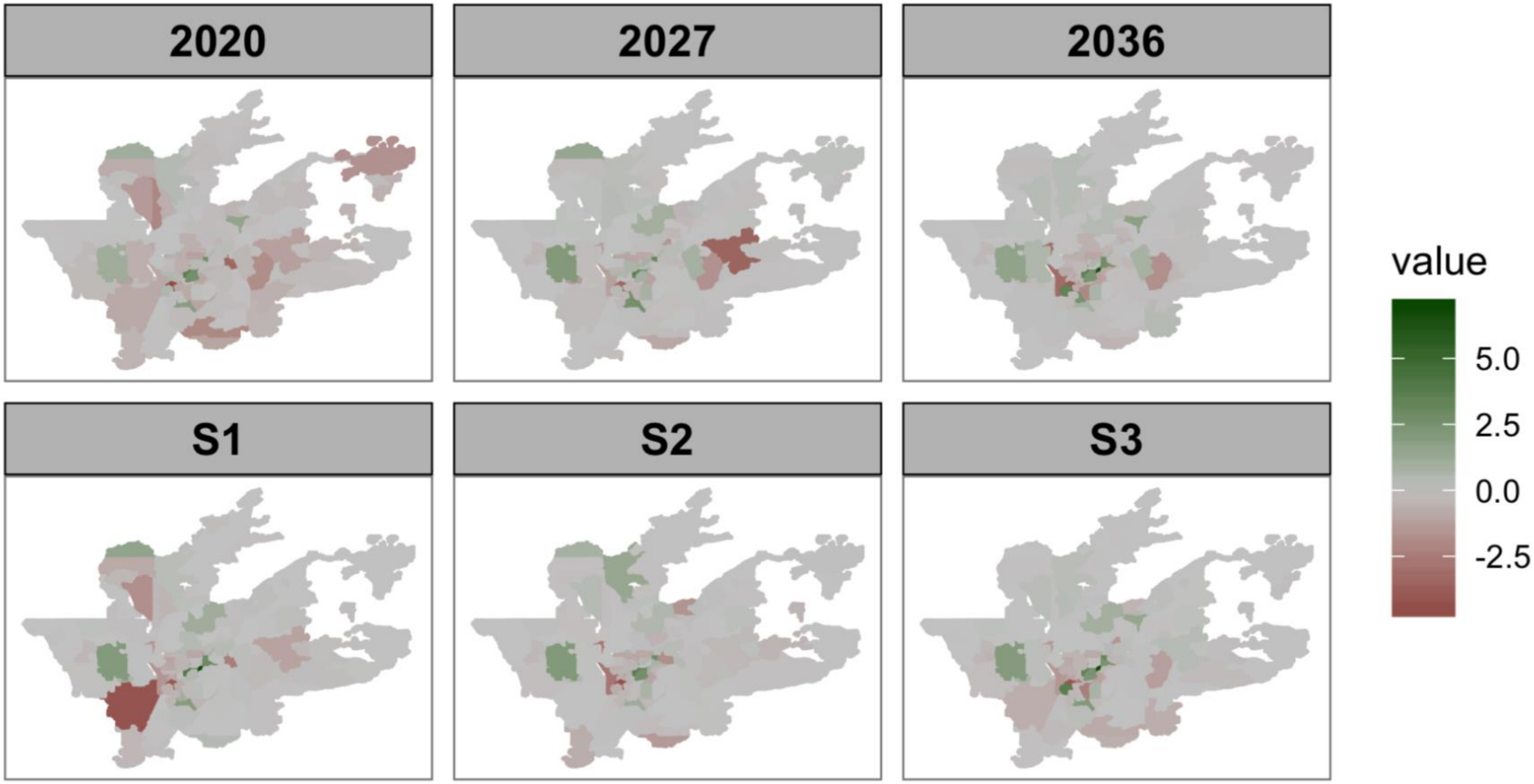

Figure 7. Total expected reduction in death from physical activity and traffic injury combined (results shown are for illustrative purposes only). The top row shows the adopted plan in 2020, 2027, and 2036. The bottom row shows Scenarios 1, 2, and 3 in 2036. Positive (green) values indicate health benefits while negative (red) values indicate worsening health outcomes.

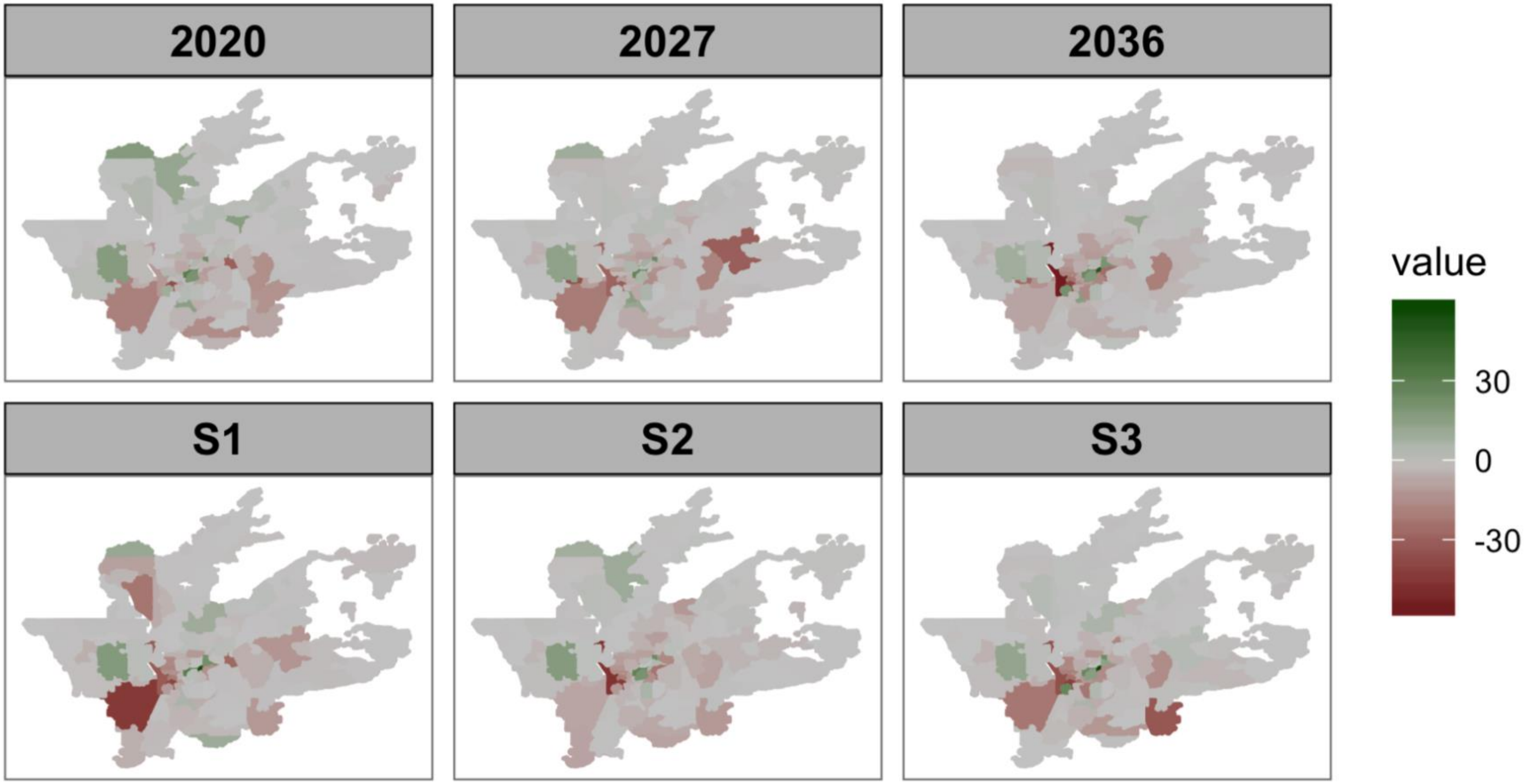

Figure 8. Total expected reduction in DALYs from changes in physical activity (results shown are for illustrative purposes only). The top row shows the adopted plan in 2020, 2027, and 2036. The bottom row shows Scenarios 1, 2, and 3 in 2036. Positive (green) values indicate health benefits while negative (red) values indicate worsening health outcomes.

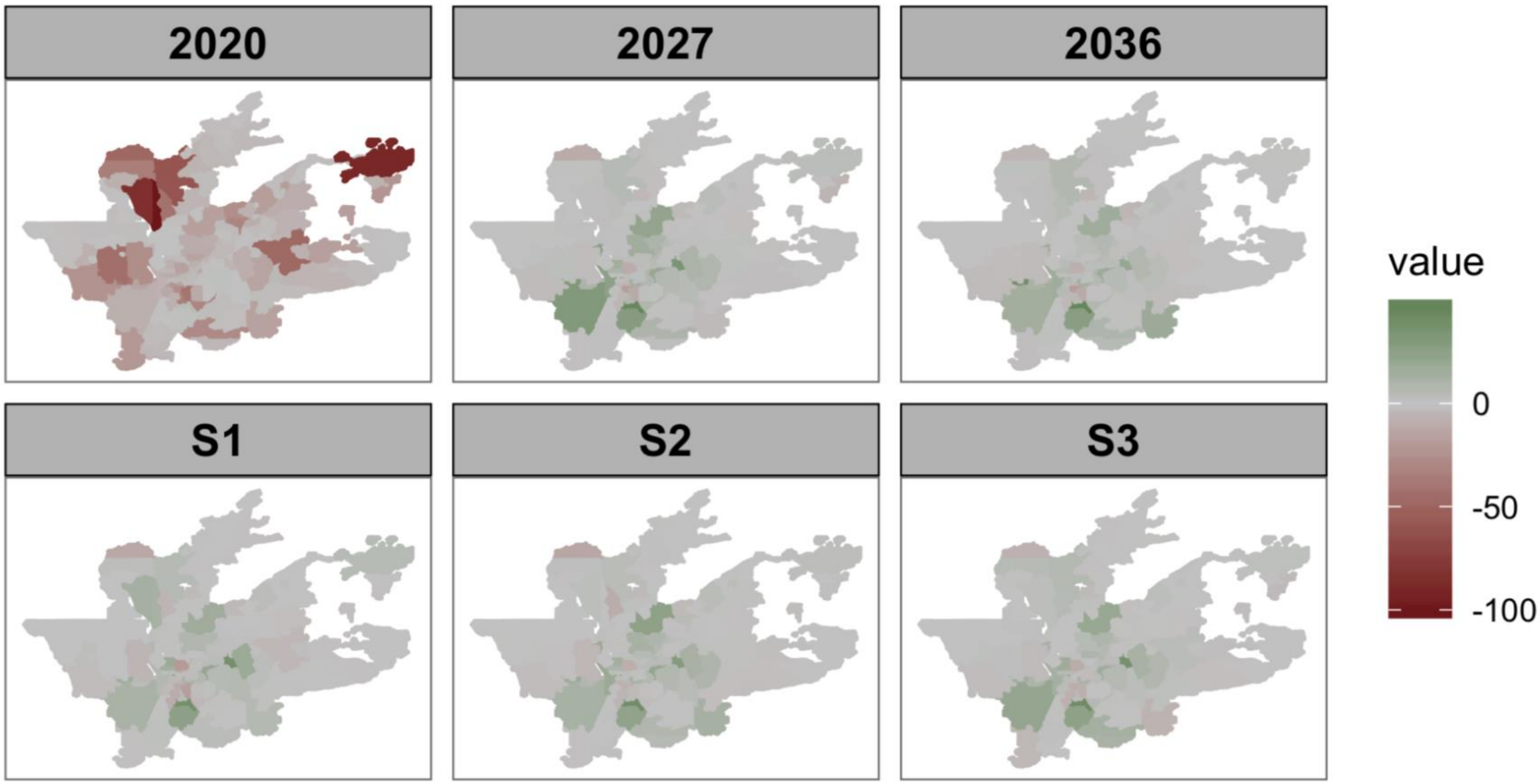

Figure 9. Total expected reduction in DALYs from traffic injury (results shown are for illustrative purposes only). The top row shows the adopted plan in 2020, 2027, and 2036. The bottom row shows Scenarios 1, 2, and 3 in 2036. Positive (green) values indicate health benefits while negative (red) values indicate worsening health outcomes.

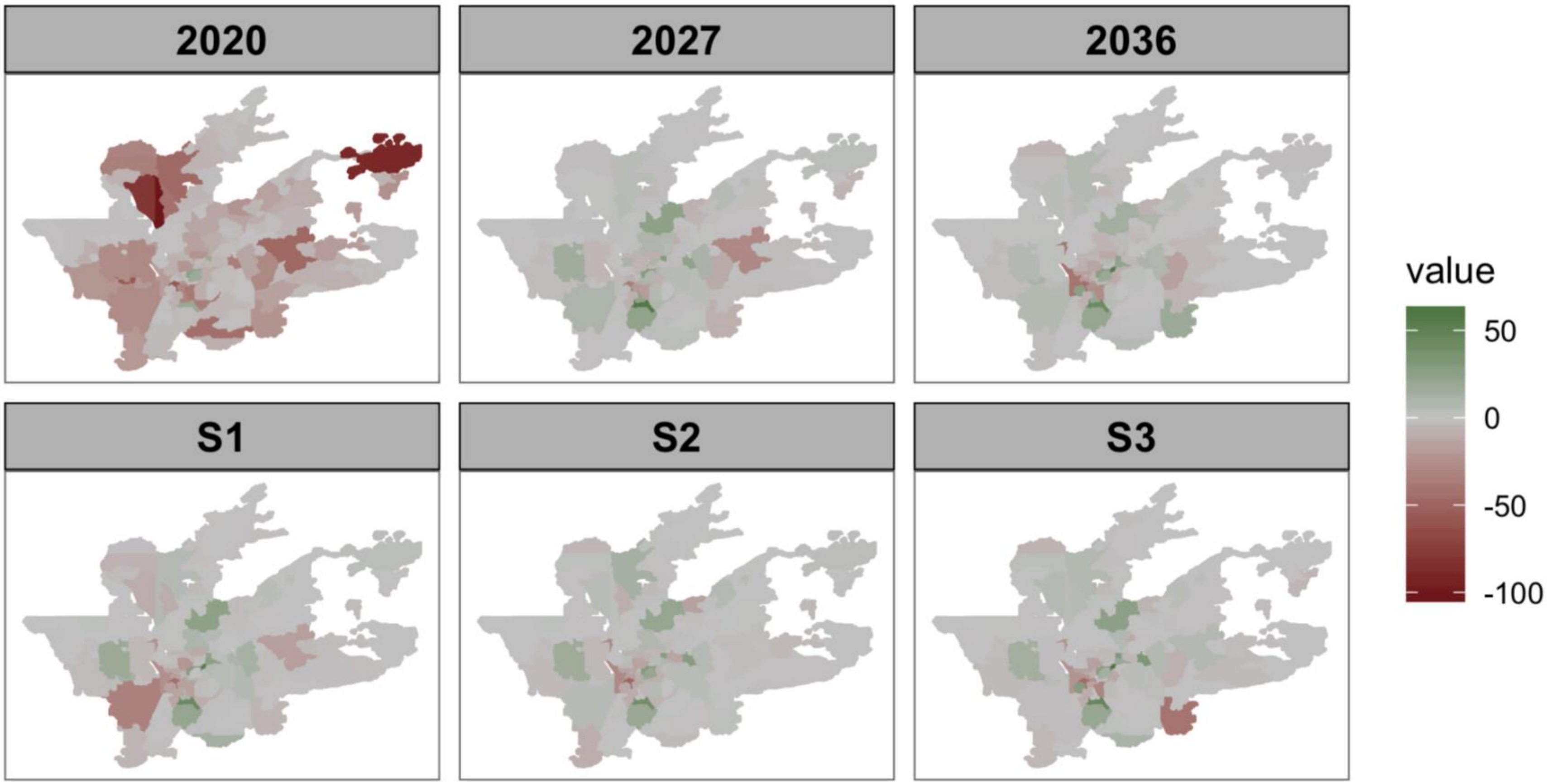

Figure 10. Total expected reduction in DALYs from changes in physical activity and traffic injury combined (results shown are for illustrative purposes only). The top row shows the adopted plan in 2020, 2027, and 2036. The bottom row shows Scenarios 1, 2, and 3 in 2036. Positive (green) values indicate health benefits while negative (red) values indicate worsening health outcomes.

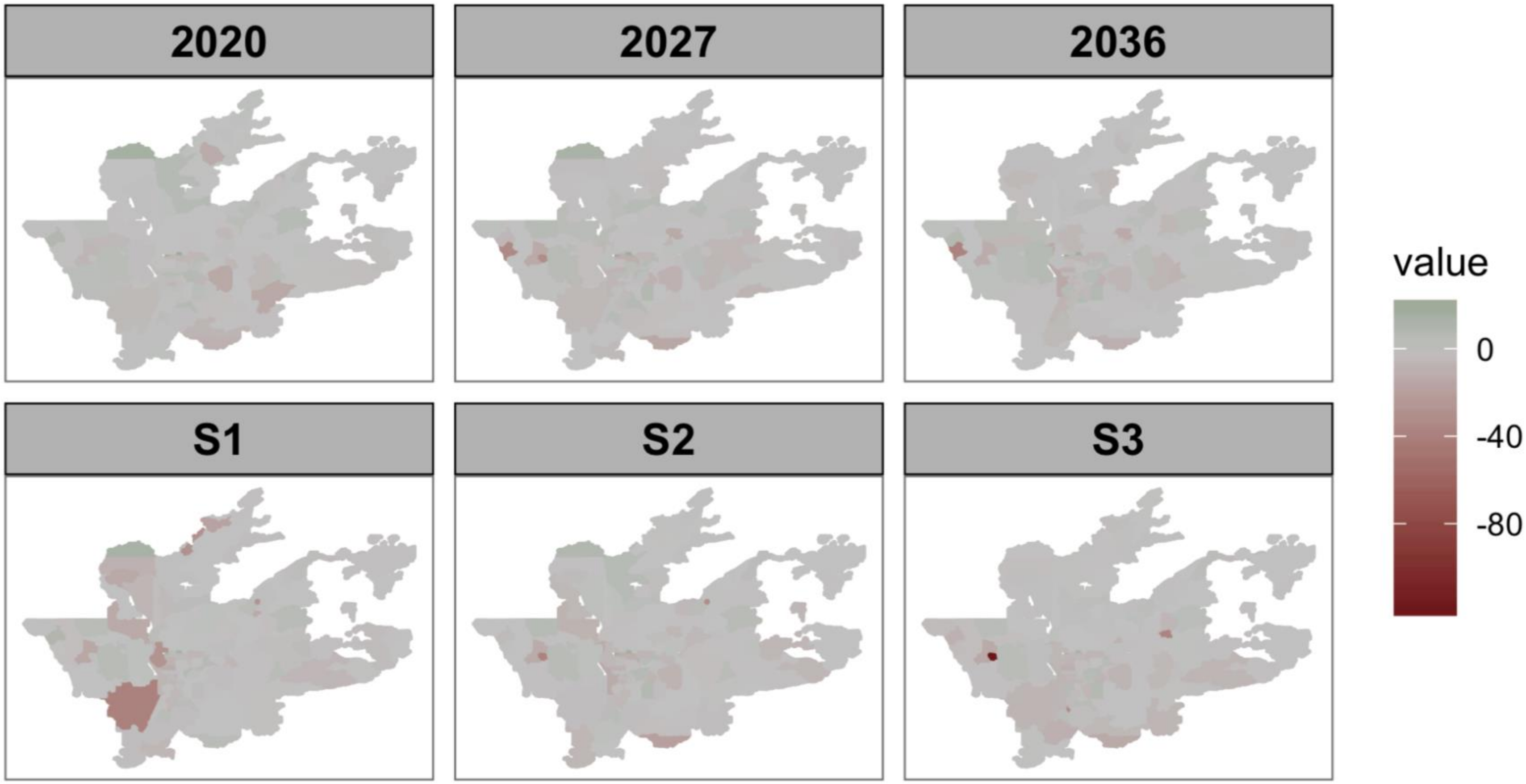

Figure 11. Expected reduction in death risk from changes in physical activity (shown as age-standardized reduction in deaths per 100,000 people (results shown are for illustrative purposes only). The top row shows the adopted plan in 2020, 2027, and 2036. The bottom row shows Scenarios 1, 2, and 3 in 2036. Positive (green) values indicate health benefits while negative (red) values indicate worsening health outcomes.

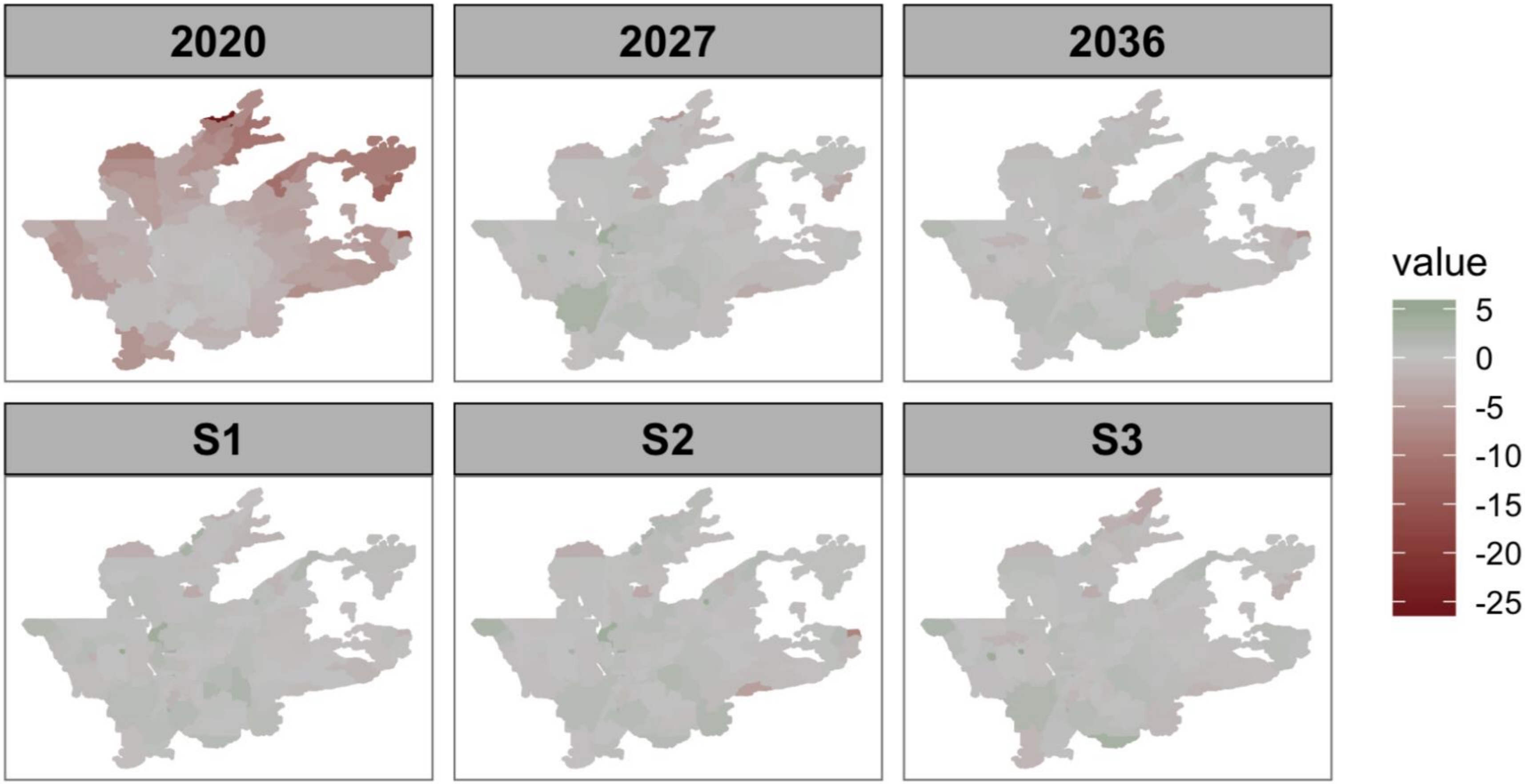

Figure 12. Expected reduction in death risk from traffic injury (shown as age-standardized reduction in deaths per 100,000 people) (results shown are for illustrative purposes only). The top row shows the adopted plan in 2020, 2027, and 2036. The bottom row shows Scenarios 1, 2, and 3 in 2036. Positive (green) values indicate health benefits while negative (red) values indicate worsening health outcomes.

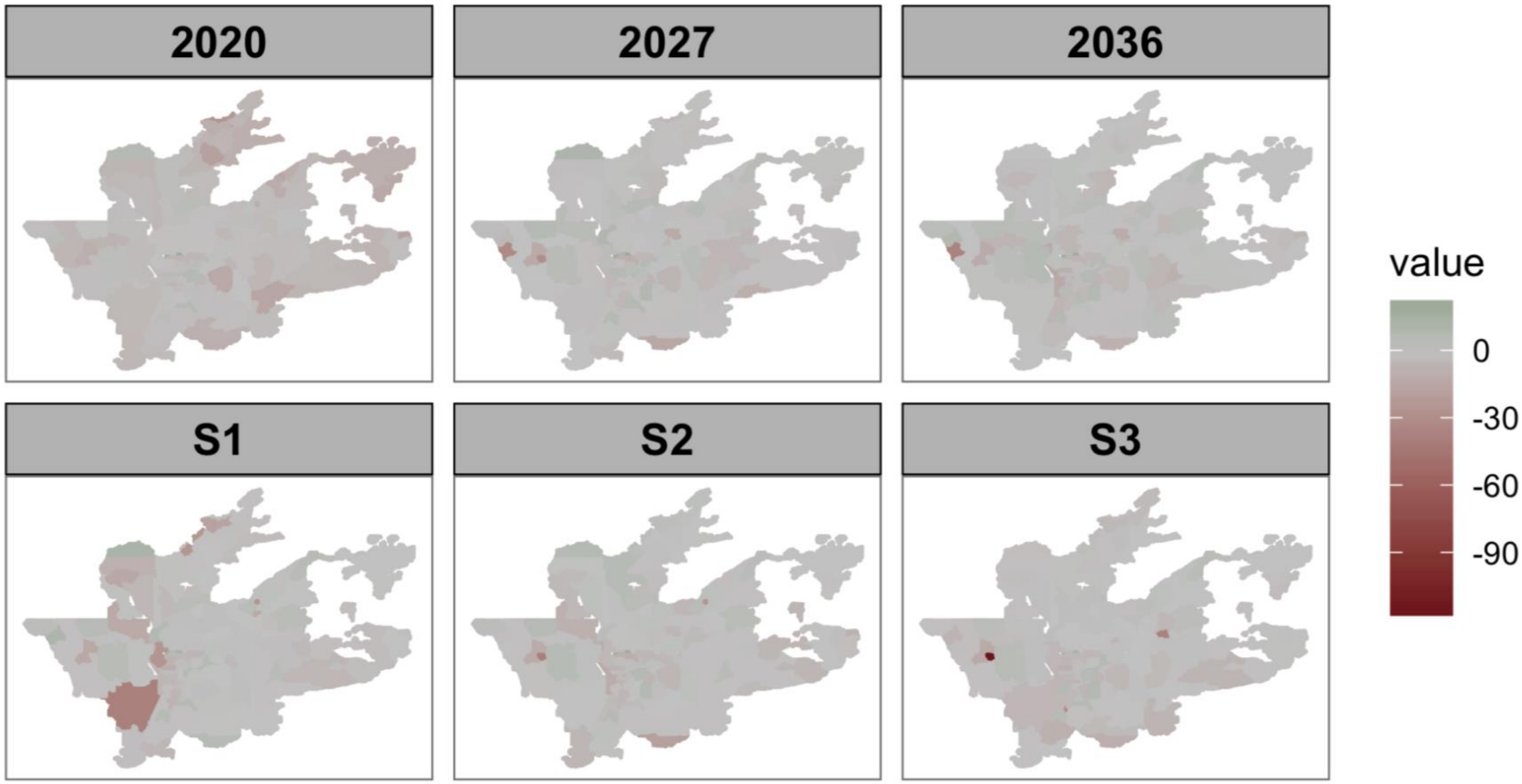

Figure 13. Expected reduction in death risk from changes in physical activity and traffic injury (shown as age-standardized reduction in deaths per 100,000 people) (results shown are for illustrative purposes only). The top row shows the adopted plan in 2020, 2027, and 2036. The bottom row shows Scenarios 1, 2, and 3 in 2036. Positive (green) values indicate health benefits while negative (red) values indicate worsening health outcomes.

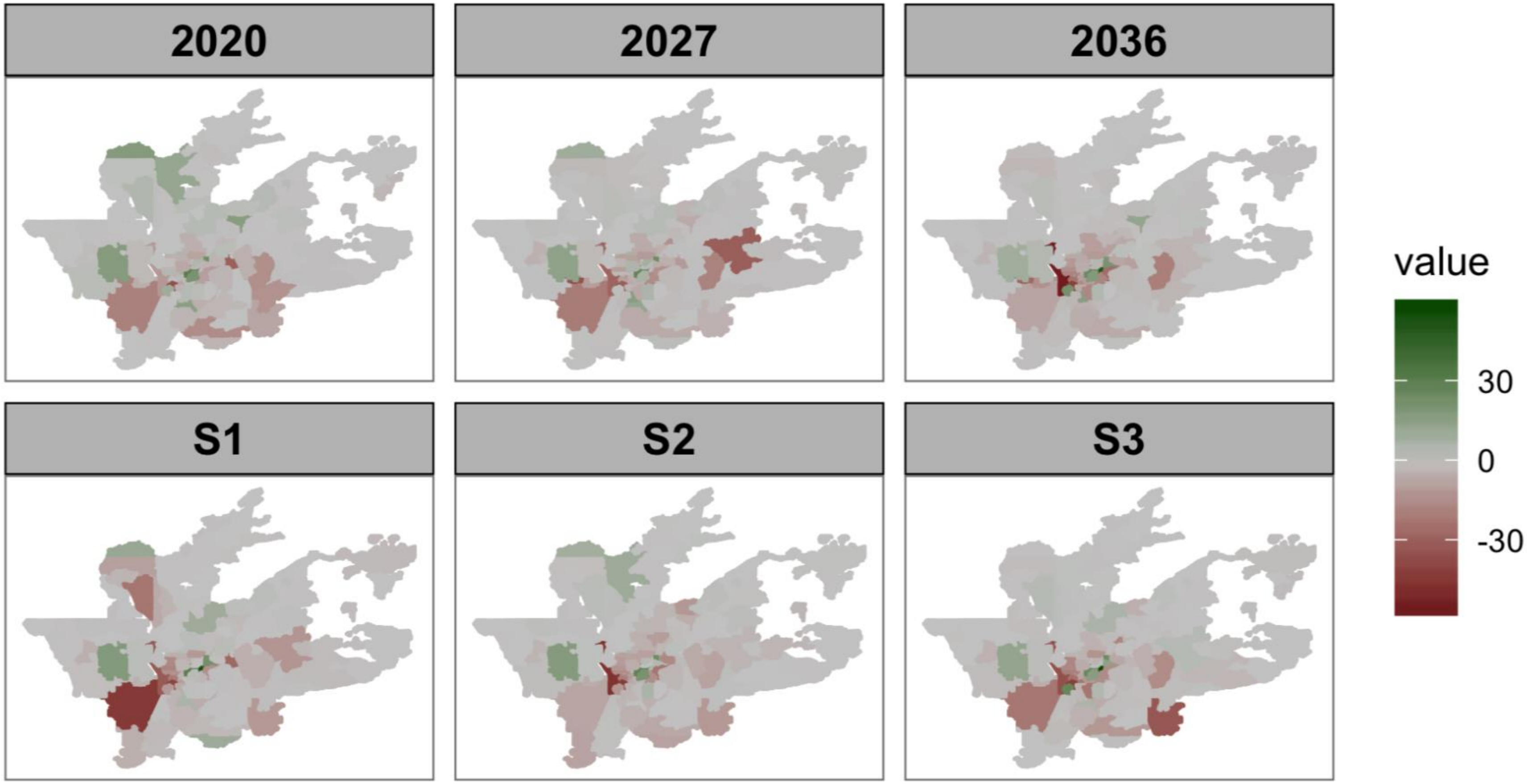

Figure 14. Expected reduction in DALYs risk from changes in physical activity (shown as age-standardized reduction in DALYs per 100,000 people) (results shown are for illustrative purposes only). The top row shows the adopted plan in 2020, 2027, and 2036. The bottom row shows Scenarios 1, 2, and 3 in 2036. Positive (green) values indicate health benefits while negative (red) values indicate worsening health outcomes.

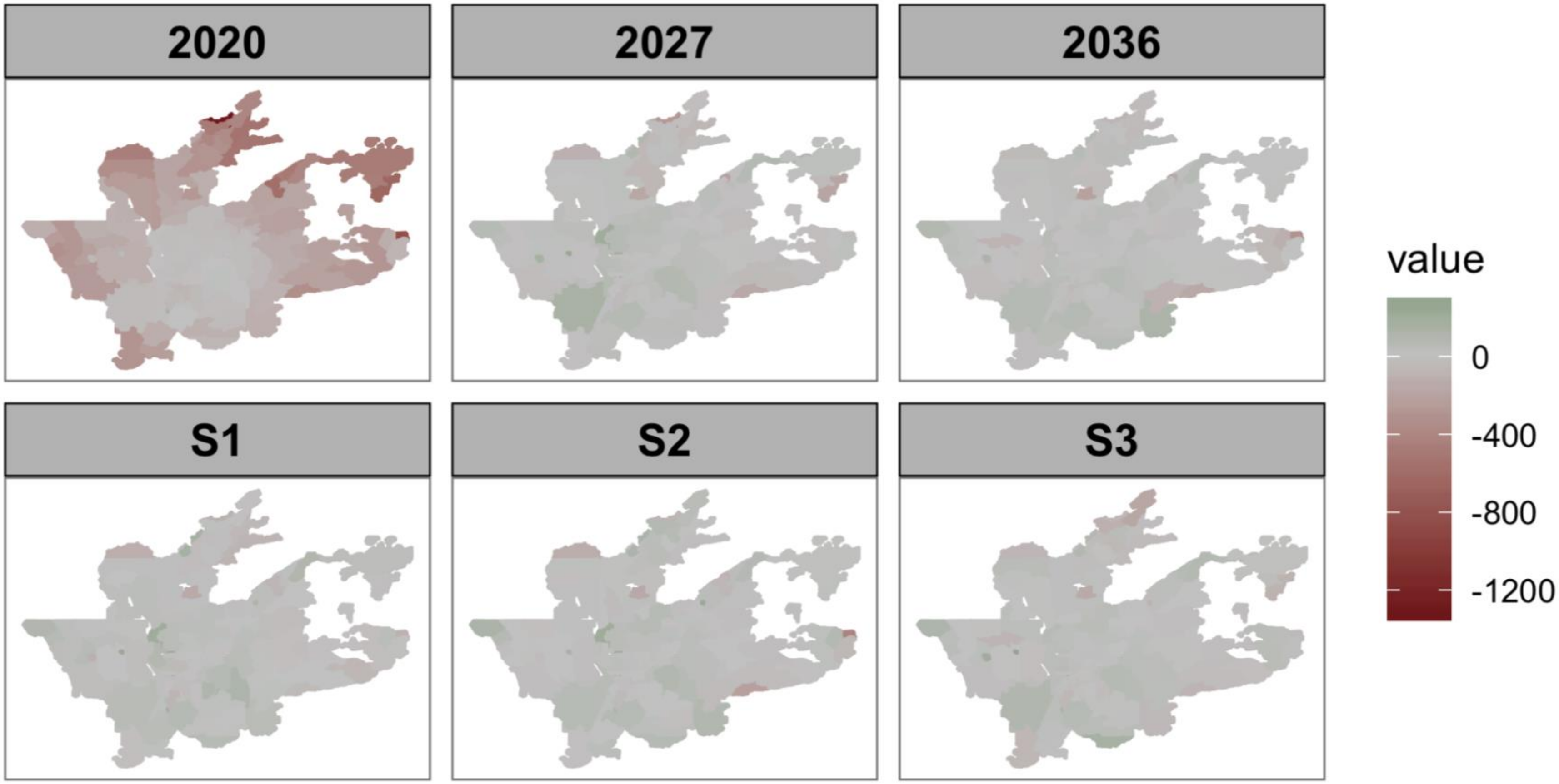

Figure 15. Expected reduction in DALYs risk from traffic injury (shown as age-standardized reduction in DALYs per 100,000 people) (results shown are for illustrative purposes only). The top row shows the adopted plan in 2020, 2027, and 2036. The bottom row shows Scenarios 1, 2, and 3 in 2036. Positive (green) values indicate health benefits while negative (red) values indicate worsening health outcomes.

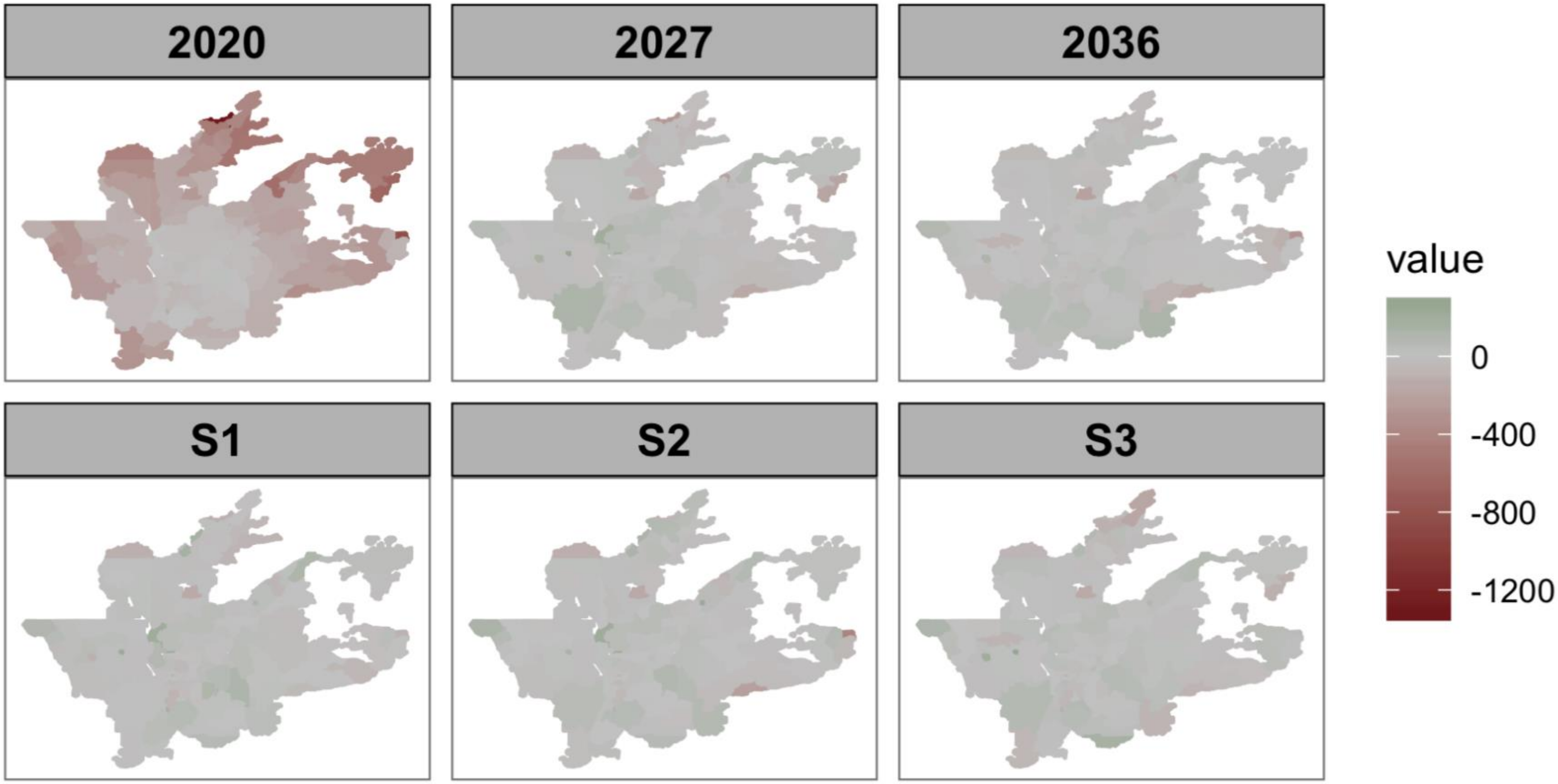

Figure 16. Expected reduction in DALYs risk from changes in physical activity and traffic injury combined (shown as age-standardized reduction in DALYs per 100,000 people) (results shown are for illustrative purposes only). The top row shows the adopted plan in 2020, 2027, and 2036. The bottom row shows Scenarios 1, 2, and 3 in 2036. Positive (green) values indicate health benefits while negative (red) values indicate worsening health outcomes.

Current Limitations and Promising Directions

As illustrated above, disaggregated health modeling has great promise for better understanding the distribution of results across communities, but it also comes with significant empirical challenges which may undermine the accuracy of disaggregated results. There are several avenues for future work which have the potential to improve the accuracy of these disaggregate model results. We recommend the following avenues for future research:

1) **Model baseline health risks at smaller spatial scales.** There is potential to improve the estimates of baseline health risks at small spatial scales using statistical modeling and sociodemographic information. This requires more detailed mortality data which takes time to obtain and process due to Health Insurance Portability and Accountability Act (HIPAA) and institutional review board requirements. The authors attempted to address this recommendation but were unable to acquire the data on the project timeline. Future model development might plan for more time to obtain and process detailed mortality data to improve small scale estimates of baseline health.
2) **Further explore travel model accuracy.** Travel demand models can have limited accuracy at small spatial scales and for non-auto modes. Additional exploration of the strengths and weaknesses of the travel demand model, and the development of strategies to mitigate their uncertainties (e.g., limited aggregation, off-model supplementation) might help to improve small area estimates of travel behavior.
3) **Model injury risks at smaller spatial scales.** The traffic injury module in ITHIM accounts for modes of travel and road type but it does not account for other factors that may be particular to a city, neighborhood, or intersection (e.g., quality of infrastructure, traveler behavior, route choice). Future refinements may incorporate additional information about community-level conditions to adjust risks spatially.
4) **Consider moderate spatial scales.** Some of these issues outlined above may not be tractable to resolve at the zip code level. Clusters of zip codes or municipal-level analysis could be explored as intermediate spatial scales to determine whether estimates at these scales are more robust to modeling noise.
5) **Perform sensitivity analysis.** There are a number of approaches to overcoming the challenges outlined above. Performing sensitivity analysis to various model formulations can increase confidence or identify limitations in modeled results.

Future Applications

With additional development, a spatially disaggregated ITHIM tool has the potential help policy makers, planners, and community advocates to visualize the health effects of different planning scenarios, which can help them to develop a shared information base to inform crucial decisions about the region’s future. With limited resources, such regional planning often entails trade-offs between different values (e.g., expansion of suburban development vs. densification of urban cores, or investments in bicycle and pedestrian infrastructure vs. roadway construction). In many cases, the public health impacts of these decisions are either not addressed or addressed too generally to guide effective decision-making. Furthermore, neighborhood-level impacts are often given limited attention. Spatially refined analysis tools can elevate the quality of the civic dialogue about how to build healthy and equitable communities and regions and the specific strategies needed to achieve this. It is recommended that leaders in the policy, planning, advocacy, business and philanthropic sectors familiarize themselves with the ITHIM methodology and explore how it can support their work, as well as exploring the potential to improve local modeling and data collection to strengthen the ability of the ITHIM model and other models' ability to understand localized effects of transportation investments. Ideally, this will occur in collaborative forums hosted by regional entities such as SACOG, the Sacramento Air Quality Management District, or area universities such as UC Davis.

Limitations

The ITHIM-Sacramento spatial analysis tool is limited by the availability of fine-grained health and non-transport travel data and the assumptions made in the analysis to overcome those limitations. The tool relies on SACSIM output for predicting travel patterns based on scenarios, which come with uncertainties. Our results illustrate the potential of spatially detailed health modeling and point to promising directions for improving model estimates, but do not fully address the challenges inherent in modeling disaggregate health outcomes.

Web Interface

Detailed model results can be viewed at https://aakarner.shinyapps.io/ITHIM-Sacramento-Spatial/. The website provides a spatial summary of the changes in health outcomes associated with SACOG's adopted plan in future years and alternative planning scenarios in 2036. Webinar materials describing the project and web tool will be made available and posted at https://doi.org/10.5281/zenodo.3424327.

Source Code and Model Documentation

All source code and model documentation for this effort are available at https://doi.org/10.5281/zenodo.3424327. This source code can be used to replicate this approach in other regions or to update the modeling for the Sacramento region. Centralized ITHIM code (which is created for more general applications) is posted at https://github.com/ITHIM/ITHIM-R.

Conclusions

The ITHIM-Sacramento spatial analysis tool combines the region's health, injury, and physical activity information with research-based relationships about the health outcomes of changes in travel behavior to estimate the health effects of future regional transportation planning scenarios. We use this modeling exercise to 1) develop a framework for evaluating ITHIM at small spatial scales; 2) illustrate the potential of understanding spatially detailed health outcomes to inform regional planning efforts; and 3) identify promising directions for improving the accuracy of disaggregate analyses of the health effects of transportation plans.

We demonstrate the ITHIM-Sacramento spatial analysis tool by evaluating expected health outcomes that are expected under SACOG's 2016 Metropolitan Transportation Plan / Sustainable Communities Strategy (MTP/SCS) scenarios and the adopted plan. The estimated health impacts for several communities in the region (broken out by zip code of residence) are presented in this report. Changes in death and disease burden (represented as DALYs) are shown as totals to understand the overall magnitude of the effects. They are also shown as age and population standardized values to facilitate comparisons across geographic areas. Total deaths can also be viewed in a user-friendly web interface that allows a user to specify the scenario shown. Our results include some unexpected findings which may be caused by the empirical challenges raised when disaggregating the analysis to small spatial scales and suggest valuable directions for future research.

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Data Management

Products of Research

All publicly available data and modeling code are available at https://doi.org/10.5281/zenodo.3424327.

Data Format and Content

Publicly available data input files are posted in .csv and commented modeling code is written in the R programming language.

Data Access and Sharing

Publicly available data and modeling code can be downloaded by the public at https://doi.org/10.5281/zenodo.3424327.

Reuse and Redistribution

Some of the raw data sets we employed require human subjects approval or data sharing agreements. These raw data do not appear on the repositories for the project. We have only posted aggregated data needed to reproduce our model results.

The published data are restricted to research use only. If the data are used, our work should be properly cited: Alex Karner. (2019, September 17). aakarner/ITHIM-Sacramento-Spatial: Archival copy (Version 0.1). Zenodo. http://doi.org/10.5281/zenodo.3424327