Applying the hypothetical extraction method to investigate the GHG emissions, water withdrawals and land use caused by Californian household food consumption.

1. *Introduction*

The global food system is a driver of water scarcity, land use change, and climate change (Foley *et al.,* 2005; Tukker *et al.,* 2006; FAO, 2011; Vermeulen *et al.,* 2012; Garnett, 2016). Despite requiring lower investments relative to other climate mitigation strategies and possessing potentially positive health and environmental externalities, food consumption patterns have been the subject of limited climate policy attention (Edenhoffer *et al*., 2014; Hallstrom *et al.,* 2017). Many studies have emphasised the strong influence that socioeconomic status has on the quantity, quality and type of food products consumed (Hulshof *et al.,* 2003; Mead *et al.*, 2010; Wrieden *et al.*, 2019; Eini-Zinab *et al.,* 2021; Franco *et al.,* 2022). The inclusion of socioeconomic variables is important for the investigation of impacts and formulating mitigation strategies as both climate change and the food system can be viewed as socio-ecological and both affect cultural values and identities which drive behaviour (Moser & Ekstom, 2010; Adger *et al.,* 2013; Bassi *et al.,* 2022).

The environmental burdens of Californian household diets have been examined by a previous study (Marlow *et al*., 2015). However, none have linked socioeconomic status to the environmental impacts. Over the last decade, California has had the highest poverty rate in the nation, and one of the largest divides between high- and low-income households among all U.S. states (Tanner, 2021; Thorman *et al.,* 2023). Although income inequality levels fell in the years following the Great Recession, this trend reversed in recent years due to the COVID-19 pandemic (Tanner, 2021; Thorman *et al.,* 2023).

To provide greater understanding of the link between the environmental impacts associated with dietary choices and levels of income inequality, we analyse the environmental burdens linked to food consumption patterns in California and allocate these impacts to different household income groups. To do this, we employ the hypothetical extraction method (HEM). HEM allows for the evaluation of an endogenous sector's contribution within an economic system. The economy-wide inter-sectorial linkages of carbon dioxide emissions have been measured with the HEM in previous studies, see WIOD countries (Ali, 2015); China (Wang *et al.*, 2013); Australia (Temurshoev, 2009); and South Africa (Zhao *et al.,* 2015); but has only been utilised once to assess the impact of personal consumption expenditure on greenhouse gas (GHG) emissions, see Perobelli *et al.* (2015). The results of this proposed attributional study may be useful for integrating environmental considerations into the design of nutrition and welfare policies.

2. *Methodology*

Assuming a region's economic system is composed of *n* sectors and *m* households, the IO model closed for households is given below:

$$x^* = A^*x^* + f^* = [I - A^*]^{-1}f^*$$

where x^* is a column vector of sectoral gross production with $(n+m)$ elements, I is an $(n+m)x(n+m)$ identity matrix, and f^* is a column vector of exogenous final demand with $(n+m)$ elements. The requirements matrix, A^*, is a matrix with $(n+m)x(n+m)$ elements, where each element, a_{ij}, reflects the share of total sectorial output for every i^{th} row and j^{th} column.

The environmentally extended input-output (EEIO) model allows for the linkages between economic activity and its embodied environmental impacts to be investigated in a single framework (Leontief, 1970; 1973). The EEIO model is described below:

$$E = \hat{e}x^* = \hat{e}[I - A^*]^{-1}f^*$$

where E is a column vector of resource and emissions flows, and the environmental coefficient vector, $\hat{e}_i$, represents the consumption-based resource requirement per dollar of output.

The purpose of the HEM is to quantify the general equilibrium effects under the hypothetical scenario where the j^{th} endogenous sector does not exist. The total extraction of sector *j* would require the rows and columns to be set to zero (Watson *et al.,* 2017). However, partial hypothetical extractions can also be derived; where either the sales or consumption structure is extracted (Perobelli *et al.,* 2015).

In this analysis, we utilise the second case where the j^{th} household group stops acquiring inputs from industrial sectors. The technical coefficient matrix is recalculated with the j^{th} column set equal to zero, A^*_{cj}, and then applied to the traditional IO relation to derive a new output vector, $\bar{x}^*_{cj}$. The difference in output before and after extraction is calculated as below:

$$\Delta x^* = \bar{x}^*_{cj} - x^* = \left([I - A^*_{cj}]^{-1}f^*\right) - ([I - A^*]^{-1}f^*)$$

Finally, the environmental impacts of the decrease in production are computed as below:

$$E^h_i = \hat{e}_i \Delta x^*_i$$

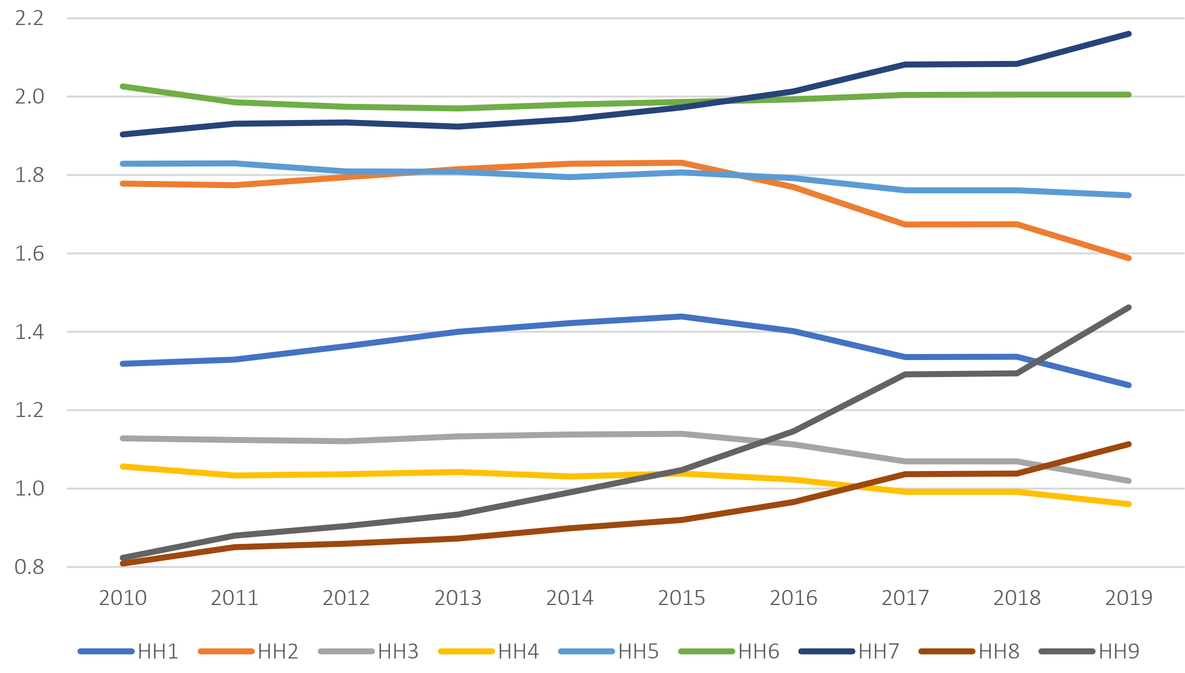
where E^h_i is a vector of the change in the environmental indictor linked to sector *i* due to the extraction of household group, *h*.

This paper utilised data on California in 2010 and 2019, which were derived from IMPLAN's IO tables and environmental satellites (IMPLAN, 2006). The estimation method for the environmental satellite data has received criticism due to its use of time-invariant consumption factors for several sectors. Nevertheless, there exists no other publicly available dataset at commensurate level of disaggregation.

The specific set of columns extracted in this analysis corresponds to the nine different household income categories specified in the IMPLAN data, see *Table.A.1*. We aggregated the sectoral structure into thirty-four new sectors, see *Table.A.2*. The typology suggested by Jorgenson *et al.* (2013) and Perobelli *et al.* (2015) with fifteen broad industrial sectors was utilised. However we retain a higher level of disaggregation for the food sector.

3. *Results*

The trends in the number of households in the nine categories (HH1-HH9) are important to discuss (*Fig.1*). As expected the shares of households in each category stayed relatively steady between 2010-2015. The modest recovery in the years following the recession low point in 2010 have been widely studied (Bohn & Danielson, 2016).



Source: Author's based on data from IMPLAN.

Fig. 1. Number of households in each income category from 2010-19. Units: Millions of households.

Between 2010 -2015, the least populous income categories were HH8 and HH9 (*Fig.1*). However, the number of households in these two categories grew from a combined 1.6 million in 2010 to 2.6 million in 2019. This growth in the two highest household income categories is consistent with the reports from the Public Policy Institute of California (PPIC) that only the highest decile income groups experienced income recovery in the years following the Great Recession (Bohn & Danielson, 2016*).*

There is evidence of growing nominal income within the lowest income categories as the share of total households within the three lowest income categories steadily declined from 33.3% in 2015 to 29.1% in 2019 (*Fig.1*). According to the California Poverty Measure (CPM), the average family of four requires $39,900 annually to remain above the poverty line (Bohn *et al.,* 2023). Thus, the trends still reflect the high rates of poverty within California.

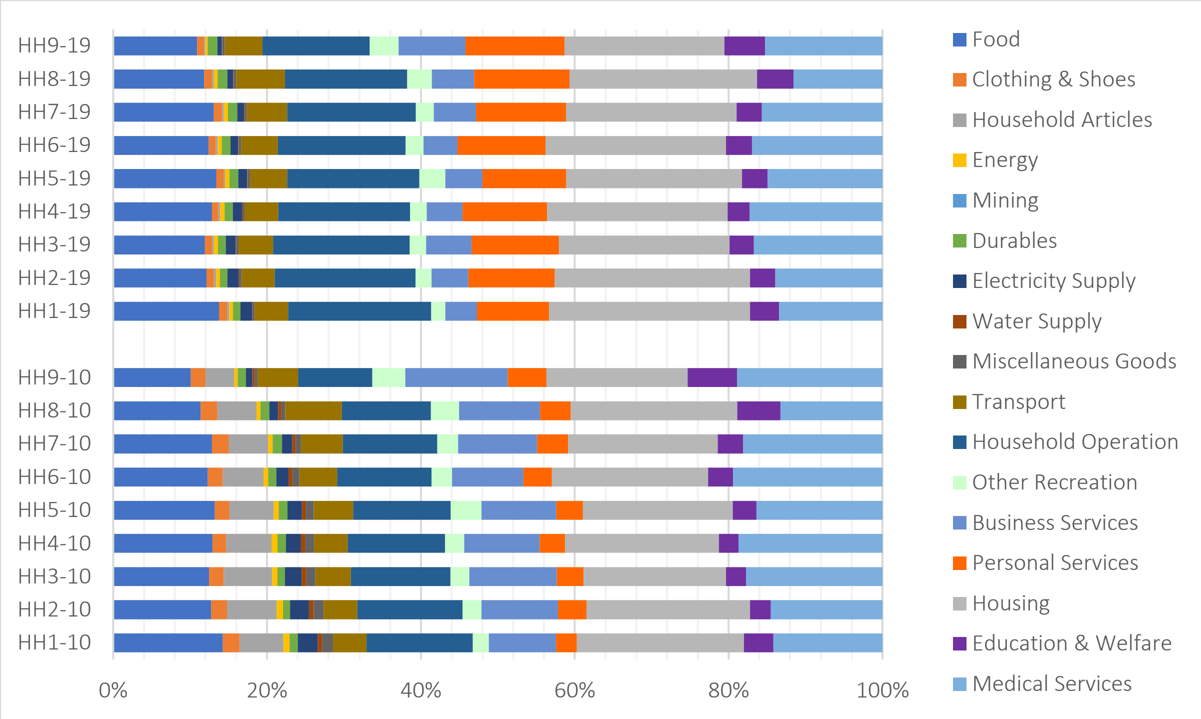
In *Fig.2*, we present the Californian household consumption structure (HCS) for 2010-2019. As expected, lower-income households spend a higher proportion of their income on basic needs (i.e. housing, food, and electricity). Given the focus of this study, we disaggregated the trends in household consumption for food-related sectors (*Fig.3*). Higher-income households spend a significantly higher share of food-related spending on non-essential goods (i.e. alcoholic beverages) relative to lower-income groups.

The majority of Californian household food-expenditure is in the hospitality sector, which is consistent with U.S.D.A. report that U.S. expenditure on hospitality has exceeded food-at-home (FAH) since 2003 (Zeballos & Sinclair, 2023). The share steadily increased for all household groups between 2010-2019. Furthermore, the share is higher among higher-income groups over the time period. However this gap reduced over time, despite the price of food-away-from-home rising in the time period and FAH experiencing price deflation in certain years (U.S.D.A., 2023).

We extract each household income group as detailed in the previous section. *Fig.4* shows the proportion of the total impact on water withdrawals, GHG emissions, and land use, due to the extraction of each household group. A surprising result is that although the results for the majority of the household groups increase with the level of income in both years, the exceptions are the lowest and the second highest income groups.

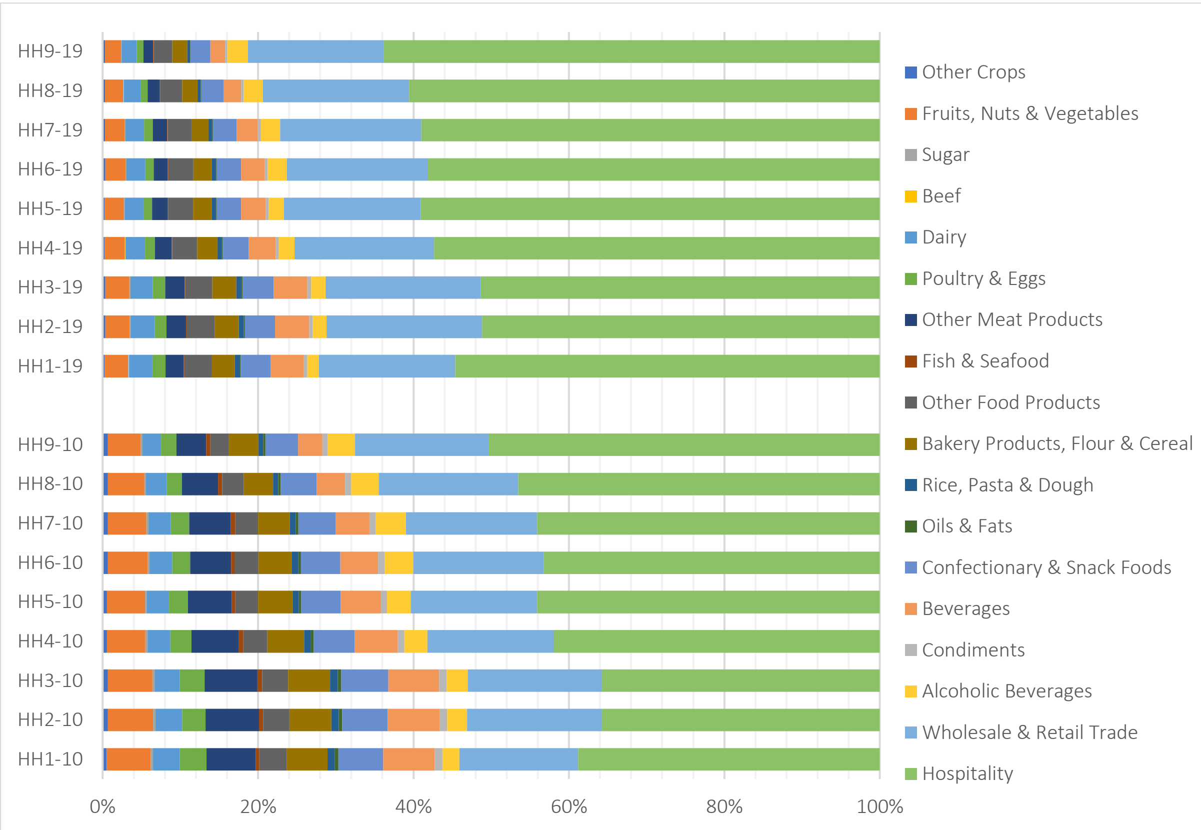
Fig.5 shows the growth rate of the impact on the annual water withdrawals, GHG emissions, and land use associated with the consumption of each household income category. Overall, there was an increase in GHG emissions, water withdrawals and land use associated with all household consumption between 2010-2019. This result holds for the food-sector and for the economy as a whole.

Extracting the household income groups separately shows that the most significant impacts can be achieved through reducing the consumption of the HH9 - over a quarter of the total impact in both years is due to the HH9 group (*Fig.4)*. Despite the population nearly doubling in the period 2010-2019, the impact of the extraction of HH9 on the environmental indicators only slightly increases from 2010-



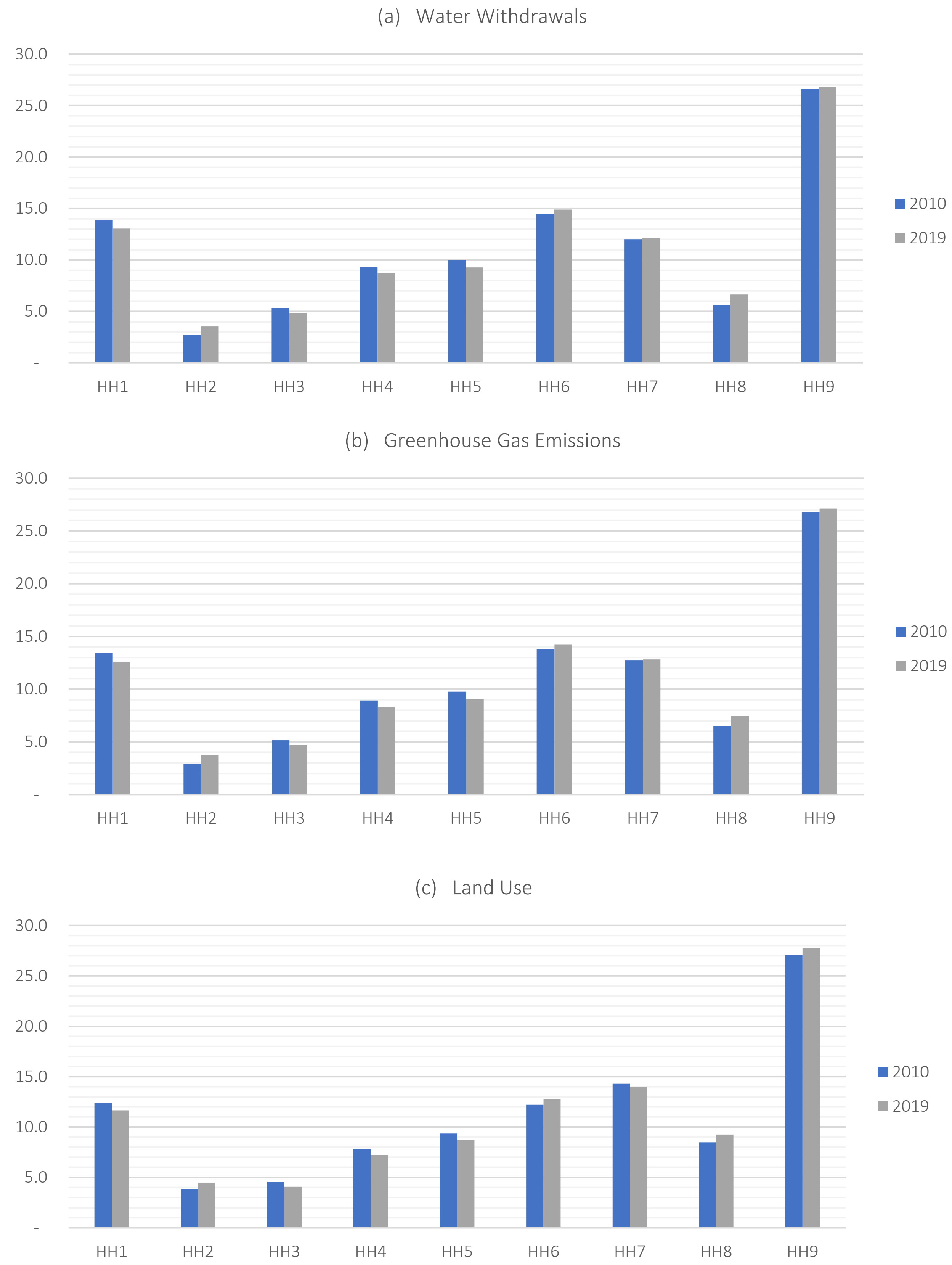
Source: Author's based on data from IMPLAN. Note: expenditure adjusted for inflation (2019 U.S. dollars).

Fig. 2. Californian household consumption structure (HCS) according to the nine IMPLAN household income categories (HH1–HH9) for 2010 and 2019.



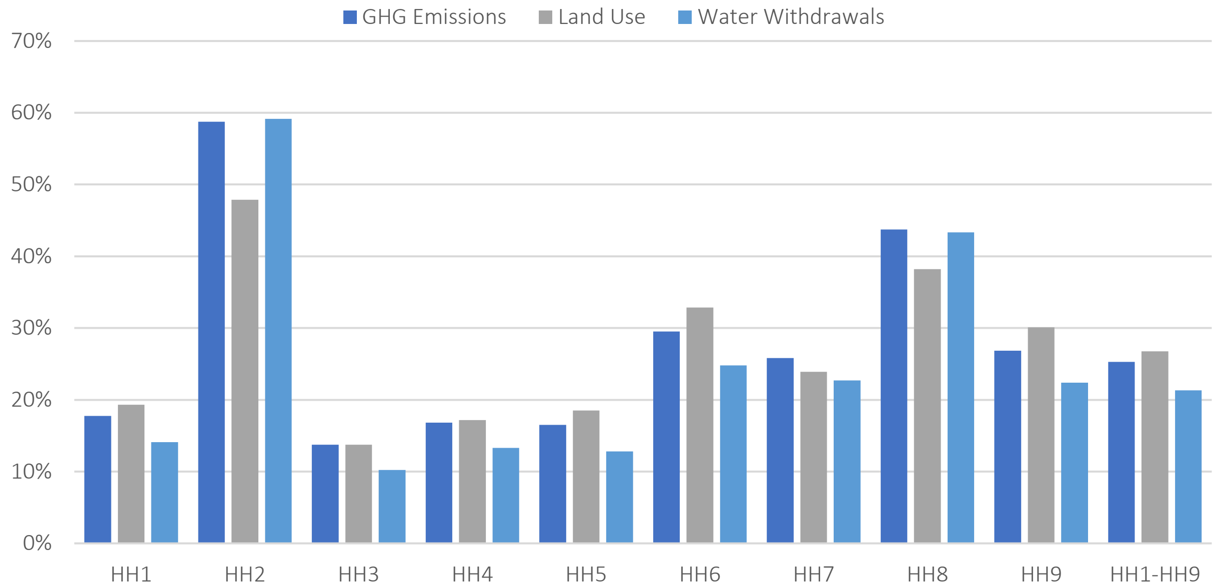
Source: Author's based on data from IMPLAN. Note: expenditure adjusted for inflation (2019 U.S. dollars).

Fig. 3. Californian food- and drink-related household consumption structure (HCS) according to the nine IMPLAN household income categories (HH1–HH9) for 2010 and 2019.



Source: Authors' calculations

Fig. 4. Share of the total decrease in the environmental indicator due to the extraction of all households associated with the extraction of each household income categories (HH1 – HH9) for 2010 and 2019. Units: percentage points.

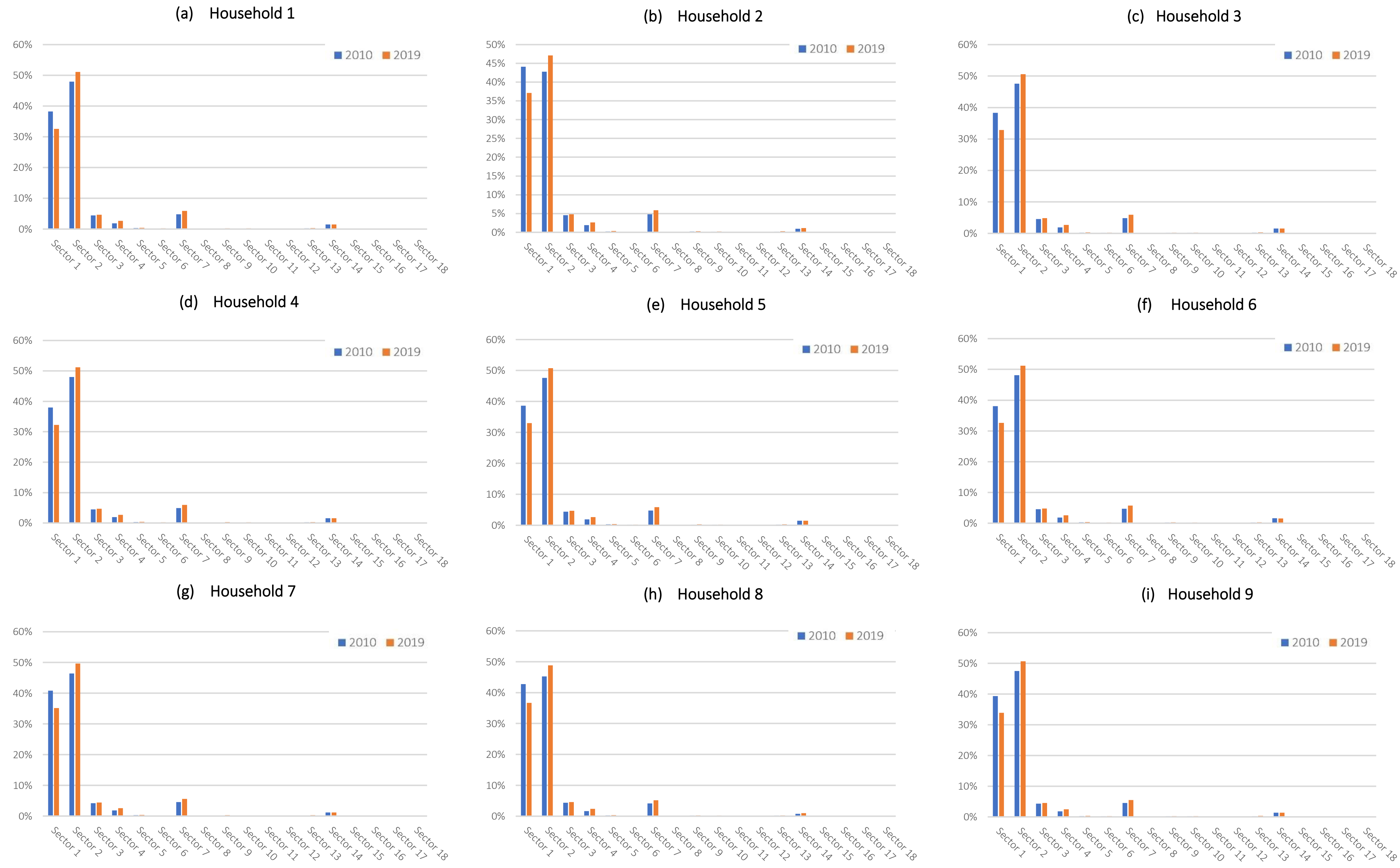


Source: Authors' calculations.

Fig. 5. The growth rates of the impacts on statewide annual GHG emissions, land use and water withdrawals produced by the extraction of each household income categories (HH1 – HH9) for 2010 and 2019. Units: percentage points.

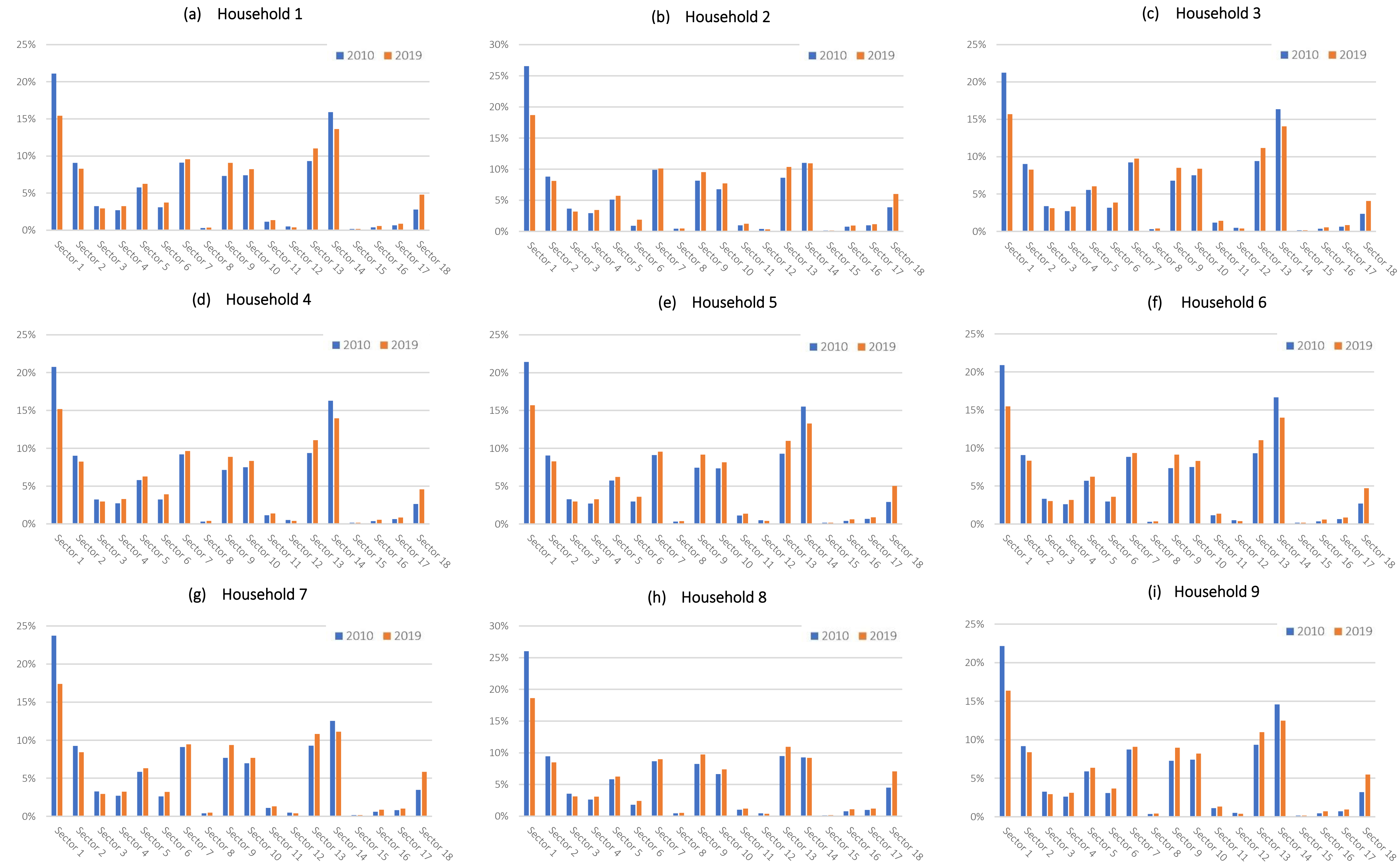
2019 (*Fig.4-5)*. In comparison, a household group that experienced a decrease in its population between 2015-2019, HH2, had the highest growth rate for all environmental impact categories between 2010-2019 (*Fig.5*). These results suggest that the variations in the HCS have resulted in more or less resource-intensive consumption between the household classes. Overall, these results suggest that if income growth implies that consumption patterns will shift toward products with lower resource use and emissions intensities, the growth in economy-wide resource use and emissions may begin to slow down.

Fig.6-8 show the impact on the annual water withdrawals, GHG emissions, and land use of food-related sectors due to the extraction of HH1-HH9, respectively. The reduction in the consumption share of fruit, nuts and vegetables; other crops; dairy; poultry; and other meat products results in these sectors being the most negatively impacted in terms of GHG emissions, land and water use. These results ascend with income levels. The one exception is that sector 2 (fruit, nuts and vegetables) is positively impacted in terms of GHG emissions between 2010-2019 for all income groups. This is expected as the water consumptive coefficient for this sector rose in the same period. The vast share of total water withdrawals related to household food consumption is associated with sectors 1 (other crops) and sector 2 (*Fig.6)*. This result is concerning as evaporative demands are projected to increase, which is expected to increase the crop irrigation requirements of these products (Peterson et al., 2023).



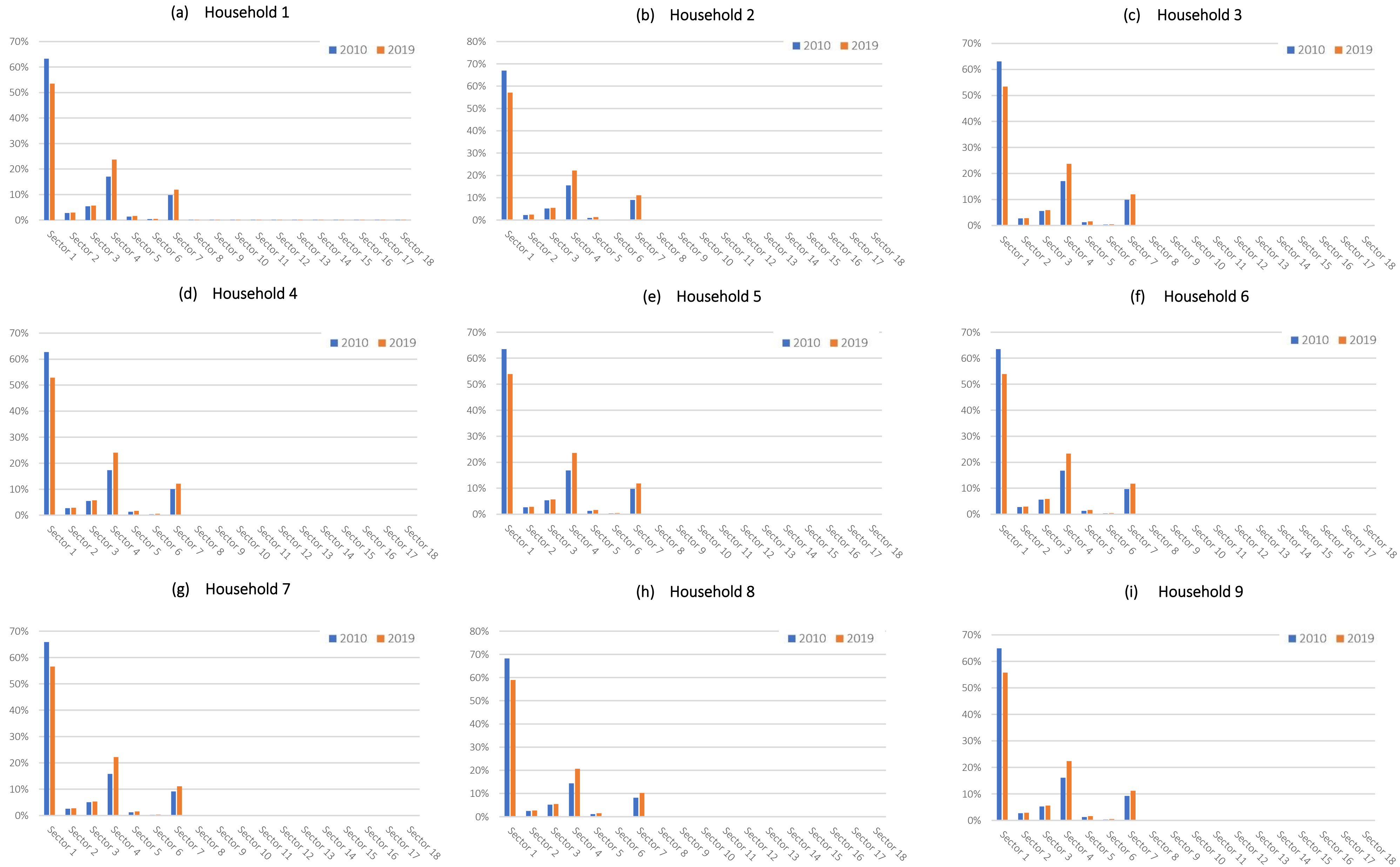
Source: Authors' calculations.

Fig. 6. The proportion of the impacts on sectorial water withdrawals according to income category.



Source: Authors' calculations.

Fig. 7. Proportion of the impacts on sectorial greenhouse gas emissions according to income category.



Source: Authors' calculations.

Fig. 8. Proportion of the impacts on sectorial land use according to income category.

More meat products (sector 4 & 7) being purchased by all household groups leads to the share of the impacts on land to increase for all HH groups between 2010-2019 (*Fig.8*). The results for GHG emissions is much less concentrated than for water and land use (*Fig.7).* Surprisingly, given the amount of attention that beef and poultry receive within climate discussions, the share for these sectors is low for all income groups.

Total household expenditure on hospitality (sector 18) out of total food-related expenditure rose between 2010-2019 (*Fig.2)*. Therefore, it is surprising, that the extraction of all household groups produces such small impacts on all three environmental indicators linked to this sector (*Fig.6-8)*. The share of hospitality in the impacts on GHG emissions only rose on average for all HH groups from 3% in 2010 to 5% in 2019. This result is consistent with the results of Reynolds *et al.* (2015) that food-away-from-home was relatively more environmentally efficient.

4. Conclusion

We employ the HEM to evaluate the contribution of household income groups to the Californian economy, and the environmental impacts of their personal consumption expenditure. As affirmed by Lenzen *et al.* (2004), natural resource depletion and environmental externalities are associated with the activities related to households. The nine different household income groups have different patterns of consumption, which is a critical explanation for the results obtained. The variation in the impacts on the environmental indicators between 2010-2019 are due to dual influences: the systematic impact on production and variation in the environmental coefficients.

The food-away-from-home sector was environmentally efficient due to its lower impact per dollar for all three environmental factors relative to the total impact per dollar spent within the food sector. Thus, tailored policies should focus on promoting 'burden-shifting' in higher-income households through the consumption of food-away-from-home.

From the HCS, we observe that for 2010 HH9's total food consumption is approximately 4.5 and 1.57 times that of HH1 and HH8, respectively. For 2019, these figures are 5.46 and 1.84, respectively. These trends support the widely held belief that, from a consumptive perspective, higher-income groups are the most vital to focus policy attention on as a minor change in the consumption of these groups could have significant impacts on the environmental indicators. The income-level growth experienced in the aftermath of the Great Recession for low-income households was insufficient to shift the share of the contribution for the three environmental impacts.

5. *Appendix*

Table A.1. Description of the household consumption structure.

	Household Income Level
HH1	<$15,000
HH2	$15,000-$30,000
HH3	$30,000-$40,000
HH4	$40,000-$50,000
HH5	$50,000-$70,000
HH6	$70,000-$100,000
HH7	$100,000-$150,000
HH8	$150,000-$200,000
HH9	>$200,000

Table A.2. Matching of the sectoral aggregation structure used in this analysis with the IMPLAN 546 Index.

	Typology	IMPLAN 546 Index
Sector 1	Other Crops	1-2; 6; 10.
Sector 2	Fruits, Nuts & Vegetables	3-5; 77; 79; 97.
Sector 3	Sugar	9; 72-73.
Sector 4	Beef Products	11.
Sector 5	Dairy Products	12; 82-85.
Sector 6	Poultry & Eggs	13; 88.
Sector 7	Other Meat Products.	14; 18; 89-91.
Sector 8	Fish & Seafood	17; 92.
Sector 9	Other Food Products	78; 80-81; 103.
Sector 10	Bakery Products, Flour & Cereal	65; 67-68; 71; 93; 96.
Sector 11	Rice, Pasta & Dough	66; 95.
Sector 12	Oils & Fats	69-70.
Sector 13	Confectionary, Desserts & Snack Foods	74-76; 86-87; 94; 98.
Sector 14	Non-alcoholic Beverages	99; 104-105.
Sector 15	Condiments	100-102.
Sector 16	Alcoholic Beverages	106-108.
Sector 17	Food-related Wholesale & Retail Trade	398; 406.
Sector 18	Food & Beverage Services.	509-511.
Sector 19	Clothing & Shoes	8; 110-131; 409.
Sector 20	Household Articles	15-16; 19; 63-64; 132-143; 154-196; 365-391.
Sector 21	Energy	20-21; 35-36; 48.
Sector 22	Mining	22-34; 37.
Sector 23	Durables	38; 50-62; 197-339.
Sector 24	Electricity	39-47.
Sector 25	Water	49.
Sector 26	Miscellaneous Goods	7; 109; 144-153;
Sector 27	Transport	340-364; 392; 402; 414-421; 512-513.
Sector 28	Household Operation	393-397; 399-401; 403-405; 407-408; 410-438; 526.
Sector 29	Other Recreation	496-508.

Sector 30	Business Services	439-446; 450-479.
Sector 31	Personal Services	514-525.
Sector 32	Housing	447-449.
Sector 33	Education & Welfare	480-482; 527-546.
Sector 34	Medical Services	483-495

6. *References*

Adger, W.N., Barnett, J., Brown, K., Marshall, N., & O'Brien, K. (2013). 'Cultural dimensions of climate change impacts and adaptation,' *Nat. Clim. Change*, 3 (2), pp.112-117, doi: 10.1038/nclimate1666.

Ali, Y. (2015). 'Measuring CO2 emission linkages with the hypothetical extraction method (HEM),' *Ecological Indicators*, 54, pp.171-183.

Bassi, C., Maysels, R., & Anex, R. (2022). 'Declining greenhouse gas emissions in the US diet (2003–2018): Drivers and demographic trends,' *Journal of Cleaner Production*, 351, doi: 10.1016/j.jclepro.2022.131465.

Bohn, S., & Danielson, C. (2016). 'Income inequality and the safety net in California.' Available at: https://www.ppic.org/wp-content/uploads/rs_archive/pubs/report/R_516SBR.pdf.

Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Farahani, E., Kadner, S., Seyboth, K., *et al.* (2014). *Climate change 2014: mitigation of climate change. In: Minx JC (ed) Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK; Cambridge University Press.

Eini-Zinab, H., Shoaibinobarian, N., Ranjbar, G., Norouzian Ostad, A., & Sobhani, S. (2021). 'Association between the socio-economic status of households and a more sustainable diet,' *Public Health Nutrition, 24* (18), pp.6566-6574, doi: 10.1017/S136898002100402X.

Food and Agriculture Organisation (FAO). (2011). *The State of the World's Land and Water Resources for Food and Agriculture—Managing Systems at Risk*. London, UK; FAO

Foley, J.A., DeFries, R.S., Asner, G.P., Barford, C., *et al*. (2005). 'Global consequences of land use,' *Science*, 309, pp.570–574, doi: 10.1126/science.1111772.

Franco, C.C., Rebolledo-Leiva, R., González-García, S., Feijoo, G., & Moreira, M.T. (2022). 'Addressing the food, nutrition and environmental nexus: The role of socio-economic status in the nutritional and environmental sustainability dimensions of dietary patterns in Chile,' *Journal of Cleaner Production*, 379 (1), doi: 10.1016/j.jclepro.2022.134723.

Garnett, T. (2016). 'Plating up solutions,' *Science*, *353*, pp.1202–1204, doi: 10.1126/science.aah4765.

Hallström, E., Gee, Q., Scarborough, P., & Cleveland, D.A. (2017). 'A healthier US diet could reduce greenhouse gas emissions from both the food and health care systems,' *Clim. Change*, 142, pp.199–212, doi: 10.1007/s10584-017-1912-5.

Hulshof, K.F.A.M., Brussaard, J.H., Kruizinga, A.G., Telman, J., & Lowik, M.R.H. (2003). 'Socio-economic status, dietary intake and 10 years trends: the Dutch national food consumption survey,' *Eur. J. Clin. Nutr.*, 57 (1), pp.128–137, doi: 10.1038/sj.ejcn.1601503.

Minnesota IMPLAN Group (IMPLAN). (2006). Available at: https://support.implan.com/hc/en-us.

Jorgenson, D.W., Goettle, R.J., Ho, M.S., & Wilcoxen, P.J. (2013). 'Energy, the environment and US economic growth.' In: Dixon, P.B., Jorgenson, D.W. (Eds.), *Handbook of Computable General Equilibrium Modeling*. North-Holland, North-Holland, Amsterdam.

Lenzen, M., Dey, C., & Foran, B. (2004). 'Energy requirements of Sydney households,' *Ecological Economics*, 49(3), pp.375-399, doi: 10.1016/j.ecolecon.2004.01.019.

Leontief, W. (1941*). The Structure of the American Economy, 1919-1929: An Empirical Application of Equilibrium Analysis*. Cambridge, MA; Harvard University Press.

Leontief, W. (1970). 'Environmental repercussions and the economic structure: an input-output approach,' *The review of economics and statistics*, pp.262-271, doi: 10.2307/1926294.

Leontief, W. (1973). 'National Income, Economic Structure and Environmental Externalities,' in: Milton Moss (ed.), *The Measurement of Economic and Social Performance.* New York, NY: Columbia University Press, pp.565-578.

Los Angeles Regional Food Bank (LARFB). (2023). 'Los Angeles County faces ongoing food insecurity challenges as rates near peak pandemic levels.' Available at: https://www.lafoodbank.org/stories/la-county-faces-ongoing-food-insecurity-challenges/#:~:text=According%20to%20a%20recent%20survey,rate%20of%2042%25%20in%202020. (Accessed June 20th, 2023).

Marlow, H. J., Harwatt, H., Soret, S., & Sabaté, J. (2015). 'Comparing the water, energy, pesticide and fertilizer usage for the production of foods consumed by different dietary types in California,' *Public Health Nutr.*, *18*, pp.2425–32, doi: 10.1017/S1368980014002833U.

Mead, E., Gittelsohn, J., Roache, C., & Sharma, S. (2010). 'Healthy food intentions and higher socioeconomic status are associated with healthier food choices in an Inuit population,' *J. Hum. Nutr. Diet.,* 23, pp.83–91, doi: 10.1111/j.1365-277X.2010.01094.x.

Moser, S.C., & Ekstrom, J.A. (2010). 'A framework to diagnose barriers to climate change adaptation,' *Proc. Nat. Acad. Sci.*, 107 (51), pp.22026-22031, doi: 10.1073/pnas.1007887107.

Perobelli, F.S., Faria, W.R., & Vale, V. (2015). 'The increase in Brazillian household income and its impact on CO2 emissions: Evidence for 2003 and 2009 from input-output tables,' *Energy Economics*, vol. 52, pp.228-239.

Peterson, C., Escriva-Bou, A., Medellin-Azura, J., & Cole, S. (2023). 'Water use in California's agriculture.' Available at: https://www.ppic.org/publication/water-use-in-californias-agriculture/ (Accessed June 15th, 2023).

Reynolds, C.J., Piantadosi, J., Buckley, J. D., Weinstein, P., & Boland, J. (2015). 'Evaluation of the environmental impact of weekly food consumption in different socio-economic households in Australia using environmentally extended input–output analysis,' *Ecological Economics*, 111, doi: 10.1016/j.ecolecon.2015.01.007.

Tanner, M.D. (2021). *An Overview of Poverty and Inequality in California.* Washington, D.C.; CATO Institute.

Temurshoev, U. (2009). 'Hypothetical extraction and fields of influence approaches: Integration and policy implications.' EERC Working Paper Series, EERC Research Network, Russia and CIS.

Thorman, T., Payares-Montoya, D., & Herrera, J. (2023). *Income inequality in California*. San Francisco, California; Public Policy Institute of California (PPIC).

Tukker, A., Huppes, G., Guinée, J., Heijungs, R., de Koning, A., van Oers, L., Suh, S., Geerken, T., *et al.* (2006). *Environmental Impact of Products (EIPRO)*. Seville, Spain; Joint Research Centre.

United States Department of Agriculture (U.S.D.A). (2023). 'Summary Findings: Food Price Outlook, 2023 and 2024.' Available at: https://www.ers.usda.gov/data-products/food-price-outlook/summary-findings/

Vermeulen, S.J., Campbell, B.M., & Ingram, J.S.I. (2021). 'Climate Change and Food Systems,' *Annual Review of Environment and Resources*, 37 (1), pp.195-222, doi: 10.1146/annurev-environ-020411-130608.

Wang, Y., Wang, W., Mao, G., Cai, H., Zuo, J., Wang, L., & Zhao, P. (2013). 'Industrial CO2 emissions in China based on the hypothetical extraction method: Linkage analysis,' *Energy Policy*, 62, pp.1238-1244.

Watson, P., Cooke, S., Kay, D., Alward, G., & Morales, A. (2017). 'A Method for Evaluating the Economic Contribution of a Local Food System,' *Journal of Agricultural and Resource Economics*, 42(2), pp.180-194.

Wrieden, W., Halligan, J., Goffe, L., Barton, K., & Leinonen, I. (2019). 'Sustainable diets in the UK – developing a systematic framework to assess the environmental impact, cost and nutritional quality of household food purchases,' *Sustainability,* 11 (18), doi: 10.3390/su11184974.

Zeballos, E., & Sinclair, W. (2023). 'US consumers spent more on food in 2022 than ever before, even after adjusting for inflation.' Available at: https://www.ers.usda.gov/amber-waves/2023/september/u-s-consumers-spent-more-on-food-in-2022-than-ever-before-even-after-adjusting-for-inflation/

Zhao, Y., Zhang, Z., Wang, S., Zhang, Y., & Liu, Y. (2015). 'Linkage analysis of sectoral CO_2 emissions based on the hypothetical extraction method in South Africa,' *J. Clean. Prod.,* 103, pp.916–924.