



### Research in context

#### Evidence before this study

Research on occupational sector disparities in COVID-19 mortality has been limited by data availability. We searched PubMed from March 1, 2020, to June 15, 2022, using the search terms “COVID-19” AND “mortality” AND “occupation”. This search yielded 474 results, which included 103 publications with substantive relevance to occupational sector disparities in COVID-19 mortality, the majority of which were focused on COVID-19 risks among health-care workers. A small number (23 studies) focused on occupational disparities in COVID-19 mortality for other essential and non-essential workers; however, only 15 of these studies measured both occupation or sector and COVID-19 infection or mortality at the individual level. The sparse available evidence that uses individual data highlights the vulnerability of older workers and suggests that COVID-19 mortality risk reflects occupational stratification, with workers in lower socioeconomic positions and migrant workers at greatest risk of death. In all studies, occupations were grouped into broad categories based on industry or sector, front-line or essential status, or risk of exposure, and then compared or modelled as a covariate. Only one study included data covering the period since widespread vaccine availability and none of the studies examined change in occupational disparities from more than one timepoint during the pandemic. Whether occupation shapes COVID-19 mortality, and how to reduce mortality disparities between workers, are not known.

#### Added value of this study

Our study considers disparities across occupational groups in SARS-CoV-2 mortality during the dominance of the delta (B.1.617.2) SARS-CoV-2 variant and during vaccine availability. We found high per-capita COVID-19 mortality in the agriculture, transportation or logistics, facilities, emergency, and manufacturing sectors. Disparities were wider during periods with a high rate of COVID-19 mortality, including during the dominance of the delta variant and during vaccine uptake. Among essential workers, per-capita COVID-19 mortality was higher among residents in regions with low vaccine uptake regions than among those in regions with high vaccine uptake, particularly during the June 27, 2021, to Nov 27, 2021 surge in infections.

#### Implications of all the available evidence

Our study is consistent with a growing body of research suggesting that workers in essential sectors face higher risks for SARS-CoV-2 infection and death than other workers. This study suggests that vaccine uptake has helped reduce these risks among essential workers; however, the levels of uptake have been insufficient to erase disparities. Increased protection of essential workers should involve increased vaccine uptake and other measures, including policies such as sick leave and workplace protections (eg, masks and ventilation).

during 2020 than those working in occupations that had the option to work from home.<sup>5</sup> Although much of the attention to occupational risks has focused on health-care workers, growing evidence on occupational disparities in COVID-19 mortality suggests that particular workers in essential sectors who are not in health care, such as transportation workers, had the highest risk of COVID-19 death in 2020.<sup>6,7</sup> It is unknown whether such disparities have continued to occur during the period of SARS-CoV-2 variants and vaccine availability.

We previously reported on COVID-19 and excess mortality by occupation in California, USA, from March 7 (the start of the pandemic) to Nov 28, 2020.<sup>1</sup> We found that people in essential sectors had an increased risk of COVID-19 and excess mortality during this period compared with those in non-essential sectors.<sup>1</sup> We also found that people working in four essential sectors—namely, food and agriculture, manufacturing, transportation and logistics, and facilities—had particularly high excess mortality. Three major contextual changes have occurred since this study was published. First, there have been surges in COVID-19 cases and deaths, led by SARS-CoV-2 variants, from December, 2020, to April, 2021, and from August to December, 2021. Second, SARS-CoV-2 vaccines became available from Dec 14, 2020, in California with prioritisation for workers in essential sectors in many jurisdictions. In California,

health-care workers were immediately prioritised for vaccination, followed by workers in other essential sectors, including food and agriculture. Third, California became less reliant on shelter-in-place restrictions—aside from a restriction from Dec 3, 2020, to Jan 25, 2021, there were no other shelter-in-place restrictions in the state in 2021. It is unclear whether disparities in COVID-19 and excess mortality have persisted throughout these changes.

The objective of this study is to examine whether disparities in excess mortality and COVID-19 mortality across occupational sectors have persisted in the face of major contextual changes to the pandemic and the pandemic response and to explore whether disparities differ by regional vaccine uptake. We add three major updates to the previous study.<sup>1</sup> We extended the time window of interest through to Nov 27, 2021, in which an increased amount of SARS-CoV-2 variants were found and vaccines became available. We additionally disaggregated data for two essential sectors that we had previously combined (health and emergency, and food and agriculture). In this Article, we note that different policies and behaviours between sectors—such as between health workers and emergency workers (first responders)—might have translated to differences in risk. We also report on differences in COVID-19 mortality between regions with low or high vaccination uptake.

## Methods

### Study design and participants

In this longitudinal cohort study, we obtained data from the California Department of Public Health, Sacramento, CA, USA, on deaths occurring in the state from Jan 1, 2016, to Dec 31, 2021. We restricted our analyses to residents of California who were aged 18–65 years (inclusive of endpoints) at the time of death and who died of natural causes. We only included participants with natural-cause deaths so that our estimates of excess mortality would more plausibly identify unrecognised or unrecorded COVID-19 deaths.

Our use of the death data was approved by the State of California Committee for the Protection of Human Subjects.

### Procedures

We identified recorded COVID-19 deaths by searching through all 20 cause-of-death variables available to us, defining a COVID-19 death as any occurrence of the code U07 of the International Classification of Diseases (tenth version). Reporting of COVID-19 deaths has been a source of controversy because people who had a suspected COVID-19 death had not been consistently tested for COVID-19. Therefore, under-reporting of COVID-19 mortality was a concern, particularly in low-socioeconomic areas and areas with more Black residents.<sup>8</sup>

Data on occupation were recorded on death certificates via free-text responses. We converted these free-text data to US Census codes using the US National Institute for Occupational Safety and Health's Industry & Occupation Computerized Coding System. A team of three researchers (Y-HC, KAD, and ARR) then categorised each unique code into one of 11 occupational sectors: agriculture, emergency services, facilities, government or community, health, manufacturing, restaurant, retail, transportation or logistics, not essential, and unemployed or missing data (this category includes homemakers, retirees, and students). The codes were initially categorised by one researcher (Y-HC); the codes were then divided among the three researchers who all audited the initial categorisations. Our choice of sectors was guided by the 13 sectors identified by California officials as comprising the state's essential workforce.<sup>9</sup> We classified three sectors from the California list as not essential: defence, communications or information technology, and financial services. We de-emphasised the defence sector because, under the California definition, it includes occupations that overlap with non-essential sectors (eg, communications and information technology), and we de-emphasised communications or information technology and financial services because they were less likely to involve on-site work during the pandemic than the other sectors. Some occupations within an essential sector did not necessarily involve on-site work during the pandemic; we did not consider this

to be misclassification in that our use of the term essential was consistent with California's definition and is always used to refer to sectors. We combined individuals with missing occupation data and individuals who were unemployed because it was difficult to differentiate between the groups via free-text response. For example, if a next of kin indicated that the occupation was unknown, it was possible that the decedent might have been, or not been, in employment. We reasoned that the small proportion of decedents with an unknown status were unlikely to meaningfully affect the results of the combined missing data or unemployed group, or any other occupational group.

### Outcomes

The primary outcomes were excess natural-cause deaths and COVID-19 deaths. A sensitivity analysis was done on the definition of high and low vaccine uptake regions.

### Statistical analysis

Our time period of interest was March 1, 2020, to Nov 30, 2021. In time-stratified analysis, we divided the time window into four phases: March 1 to Nov 28, 2020 (phase 1); Nov 29, 2020, to Feb 27, 2021 (phase 2); Feb 28 to June 26, 2021 (phase 3); and June 27 to Nov 27, 2021 (phase 4). Vaccines became available to health workers in California near the beginning of phase 2, whereas vaccines became available to emergency workers and workers in other essential sectors near the beginning of phase 3.<sup>10</sup> Phase 2 and phase 4 correspond to surges in COVID-19 cases and deaths.

In the secondary analysis, we stratified by California counties with low or high vaccine uptake among working-age individuals, using data from the US Centers for Disease Control and Prevention.<sup>11</sup> We defined counties with low vaccination as counties with less than 50% of the population fully vaccinated according to US guidelines by Aug 1, 2021. High vaccine uptake counties were defined as counties with 50% or more uptake of full vaccination by Aug 1, 2021.

In a sensitivity analysis, we employed an alternative cutoff point that would improve the consistency of the low and high vaccine uptake definition over time. For the cutoff of the sensitivity analysis, we defined counties with a high uptake of vaccination as the 15 counties with the highest uptake on Aug 1, 2021. Low-uptake counties were defined as those not in the top 15 of vaccine uptake on Aug 1, 2021. Because differences between occupational sectors could be affected by differences in age and sex, we also did a sensitivity analysis with age-stratified (18–35 years, 36–55 years, and 56–65 years) and sex-stratified (male or female) data.

For each group of interest: we calculated the number of COVID-19 deaths occurring in total and per capita—that is, divided by the estimated population size of the group—in each week, over the entire time window, and in each phase; we obtained subgroup-specific population

	Deaths from COVID-19			Excess deaths		
	Population size*	Total deaths	Deaths per 100 000 people	Total (95% prediction interval)	Per capita† (95% prediction interval)	Relative (95% prediction interval)
Entire state	25 220 309	24 799	56.2	28 751 (27 853–29 653)	65.1 (63.1–67.2)	1.31 (1.30–1.33)
Agriculture	438 722	1012	131.8	1223 (1148–1298)	159.3 (149.6–169.1)	1.61 (1.55–1.67)
Emergency services	419 799	645	87.8	756 (667–845)	102.9 (90.7–115.0)	1.40 (1.33–1.47)
Facilities	2 557 851	4527	101.1	5487 (5147–5826)	122.6 (115.0–130.2)	1.37 (1.34–1.40)
Government or community	2 312 880	1592	39.3	1917 (1680–2151)	47.4 (41.5–53.1)	1.29 (1.24–1.33)
Health	1 604 590	1065	37.9	1003 (864–1141)	35.7 (30.8–40.6)	1.21 (1.18–1.25)
Manufacturing	1 156 113	2089	103.3	1954 (1816–2091)	96.6 (89.8–103.4)	1.37 (1.33–1.40)
Restaurant	1 447 496	1344	53.1	1882 (1639 to 2121)	74.3 (64.7 to 83.7)	1.46 (1.38 to 1.55)
Retail	1 582 935	1262	45.6	1443 (1302–1583)	52.1 (47.0–57.1)	1.28 (1.25–1.32)
Transportation or logistics	1 803 861	3381	107.1	4160 (3963–4356)	131.8 (125.5–138.0)	1.45 (1.42–1.48)
Not essential	7 804 074	3761	27.5	3702 (2243–5128)	27.1 (16.4–37.5)	1.17 (1.10–1.26)
Unemployed or missing data	4 091 988	4121	57.5	4876 (4602–5150)	68.1 (64.3–71.9)	1.29 (1.27–1.31)

\*Estimated population size. †Data annualised.

**Table 1: Excess natural-cause mortality among individuals aged 18–65 years who are residents in California, by occupational sector, March 1, 2020, to Nov 27, 2021**

estimates, for the per-capita numbers, from the 2019 ACS, which was a large, randomised sample of US addresses administered by the US Census Bureau; and we fitted dynamic harmonic regression models with autoregressive integrated moving average errors for the number of deaths per week,<sup>12</sup> using deaths occurring in the group between Jan 3, 2016, and Feb 29, 2020 (ie, before the surge of COVID-19 cases). Using the resulting model, we forecasted the number of deaths for each unit of time, along with corresponding 95% prediction intervals. To obtain the total number of excess deaths for the entire time window and during each phase, we subtracted the total number of expected deaths from the total number of observed deaths. We obtained a 95% prediction interval for the total by simulating the model 10 000 times, selecting the 97.5% and 2.5% quantiles, and subtracting from the total number of observed deaths.

In addition to the estimated number of excess deaths (calculated as the observed number of deaths minus expected number of deaths), we calculated and report excess deaths per capita. Excess deaths per capita was calculated with the observed number of deaths minus the expected number of deaths, divided by the estimated population size. We calculated relative excess mortality as the observed number of deaths divided by the expected number of deaths. A relative excess mortality ratio of 1.5 would indicate that there were 50% more deaths observed during the pandemic than we would have expected had the pandemic not occurred. Per-capita excess mortality can be interpreted as a risk difference for mortality, whereas relative excess can be interpreted as a risk ratio for mortality. In both cases, the comparison

is between the pandemic and non-occurrence of the pandemic (the reference group is non-occurrence of the pandemic).

Our reported deaths per-capita data are annualised, obtained by dividing the per-capita measure by the number of weeks and multiplying by 52. We did all analyses in R (version 4.1.3).

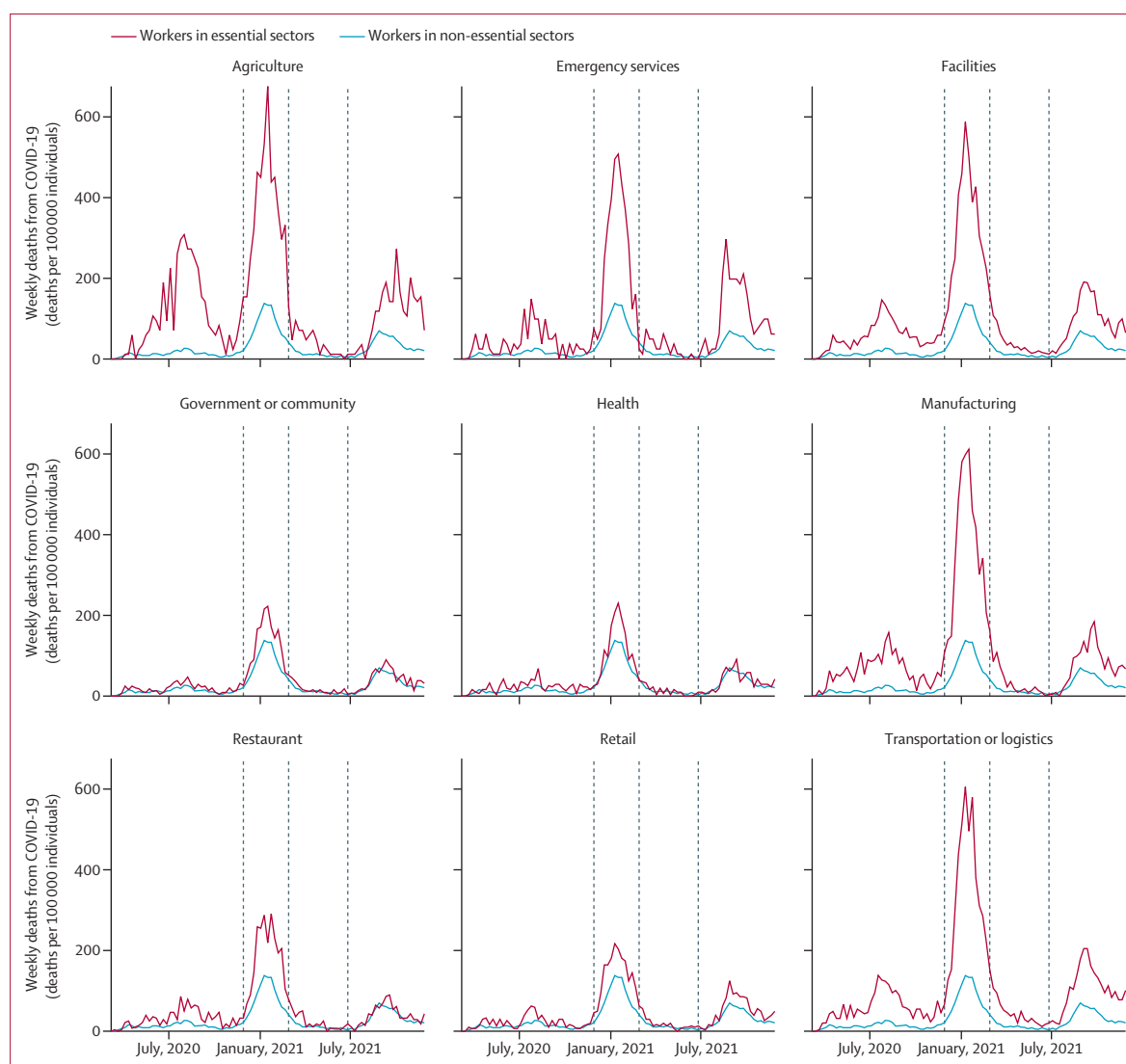
### Role of the funding source

The funders of the study had no role in study design, data collection, data analysis, data interpretation, or writing of the report.

### Results

There were 342 625 deaths reported among individuals who were residents in California between Jan 3, 2016, and Nov 27, 2021. Between March 1, 2020, and Nov 27, 2021, there were 24 799 COVID-19 deaths reported among people aged 18–65 years who were residents in California and an estimated 28 751 (95% prediction interval 27 853–29 653) excess deaths (table 1). We focus on our findings on COVID-19 deaths and view the estimates of excess mortality as sensitivity checks of the COVID-19 deaths, particularly given discrepancies between COVID-19 mortality and estimated excess mortality early in the pandemic, which we believe to be primarily due to unrecognised or unreported COVID-19 deaths.

Across occupational groups, workers in the agriculture, transportation or logistics, manufacturing, facilities, and emergency sectors had the highest per-capita COVID-19 mortality, per-capita excess mortality, and relative excess mortality. Among agriculture workers, there were



**Figure 1: Per-capita COVID-19 mortality among individuals aged 18–65 years living in California, by occupational sector**

Data from March 1, 2020, to Nov 27, 2021. Data are annualised. Dashed vertical lines differentiate the four phases of the analysis. Phase 2 and phase 4 correspond to surges in COVID-19 cases and deaths.

131·8 reported COVID-19 deaths per 100 000 people and an estimated 159·3 (95% prediction interval 149·6–169·1) excess deaths per 100 000 people; the relative excess mortality among agriculture workers was 1·61 (1·55–1·67). Workers in non-essential sectors had the lowest per-capita COVID-19 mortality (27·5 deaths per 100 000), per-capita excess mortality (27·1 [16·4 to 37·5] deaths per 100 000), and relative excess mortality (1·17 [1·10–1·26] deaths per 100 000).

We classified 27 counties as having a high vaccine uptake and 23 counties as having a low vaccine uptake. Although our definition was somewhat arbitrary, differentiation between the high-uptake and low-uptake counties was fairly consistent for 95 continuous days. The appendix (p 1) shows vaccine uptake in each of the 50 counties included in the analysis. At the end of the

study period, the median vaccine uptake was 73·0% (range 60·4–89·0%) in high-uptake counties and 56·6% (range 31·6–66·8%) in low-uptake counties.

Per-capita COVID-19 mortality varied over time, peaking in phase 2 (from Nov 29, 2020, to Feb 27, 2021) and in phase 4 (June 27 to Nov 27, 2021; figure 1). Across time, there were disparities in per-person COVID-19 mortality between workers in essential sectors and workers in non-essential sectors; these persisted across the four phases of the analysis. The differences were particularly large when comparing workers in non-essential sectors to workers in the agriculture, emergency, facilities, manufacturing, and transportation or logistics sectors.

During the Nov 29, 2020, to Feb 27, 2021 surge in deaths (phase 2), per-capita COVID-19 mortality

See Online for appendix



	Phase 1			Phase 2			Phase 3			Phase 4		
	Deaths from COVID-19 per 100 000 people	Rank	Risk difference*	Deaths from COVID-19 per 100 000 people	Rank	Risk difference*	Deaths from COVID-19 per 100 000 people	Rank	Risk difference*	Deaths from COVID-19 per 100 000 people	Rank	Risk difference*
Entire state	29.9	..	..	182.9	..	..	20.1	..	..	55.8	..	..
Agriculture	103.6	1	91.5	373.8	1	288.7	37.6	2	26.7	111.5	2	77.9
Emergency services	40.0	5	27.9	269.7	5	184.5	24.8	5	13.8	113.7	1	80.1
Facilities	55.6	4	43.4	330.9	4	245.8	36.0	3	25.1	96.5	4	62.9
Government or community	18.1	10	5.9	130.9	9	45.8	15.5	9	4.5	41.3	8	7.7
Health	21.9	8	9.7	119.9	10	34.8	12.2	10	1.3	37.9	10	4.3
Manufacturing	61.4	2	49.2	367.8	2	282.6	29.6	4	18.7	78.1	5	44.5
Restaurant	30.2	7	18.0	186.5	7	101.4	20.1	7	9.1	40.2	9	6.6
Retail	21.6	9	9.4	143.8	8	58.6	16.4	8	5.5	52.6	7	19.0
Transportation or logistics	55.9	3	43.7	350.8	3	265.7	40.5	1	29.6	105.3	3	71.8
Not essential	12.2	11	Ref	85.1	11	Ref	10.9	11	Ref	33.6	11	Ref
Unemployed or missing data	31.3	6	19.1	189.2	6	104.1	20.6	6	9.7	54.8	6	21.2

Data are annualised. Rank indicates the rank of the per-capita COVID-19 mortality from highest to lowest. Phase 1: March 1 to Nov 28, 2020; phase 2: Nov 29, 2020, to Feb 27, 2021; phase 3: Feb 28 to June 26, 2021; and phase 4: June 27 to Nov 27, 2021. \*The difference in deaths from COVID-19 per 100 000 relative to workers in non-essential sectors.

**Table 2: Deaths from COVID-19 per 100 000 among individuals aged 18–65 years who are residents in California, by occupational sector and phase, March 1, 2020, to Nov 27, 2021**

was highest among workers in the agriculture (373.8 deaths per 100 000 people), manufacturing (367.8 deaths per 100 000), transportation or logistics (350.8 deaths per 100 000), facilities (330.9 deaths per 100 000), and emergency services (269.7 deaths per 100 000 people) sectors (table 2). These sectors all had reduced per-capita COVID-19 mortality during phase 4. Absolute disparities in per-capita COVID-19 mortality between workers in essential sectors and workers in non-essential sectors increased during a period of time when vaccines were available, during the June 27 to Nov 27, 2021 surge (phase 4). For example, the absolute disparity between transportation or logistics workers and workers in non-essential sectors was 29.6 deaths per 100 000 people during phase 3 and 71.8 deaths per 100 000 people during phase 4. Similarly, between phase 3 and phase 4, the absolute disparity between agriculture workers and workers in non-essential sectors increased from 26.7 deaths per 100 000 people to 77.9 deaths per 100 000 people.

On a relative scale, disparities between workers in essential sectors and workers in non-essential sectors generally decreased over time. For example, over the four phases of our analysis, COVID-19 relative excess mortality among workers in the manufacturing sector was 5.04, 4.32, 2.71, and 2.33 times that among workers in non-essential sectors in phase 1, phase 2, phase 3, and phase 4, respectively (data not shown). This decline was not observed among emergency workers: the relative disparity in per-capita COVID-19 mortality between emergency sectors and workers in non-essential sectors was 3.29 in phase 1, 3.17 in phase 2, 2.27 in phase 3, and 3.39 in phase 4. There were also increases in the relative

disparity in per-capita COVID-19 mortality between emergency services workers and health workers; this discrepancy was 1.83 in phase 1, 2.25 in phase 2, 2.03 in phase 3, and 3.00 in phase 4. Emergency services emerged during phase 4 as the sector with the highest per-capita COVID-19 mortality (113.7 per 100 000 people).

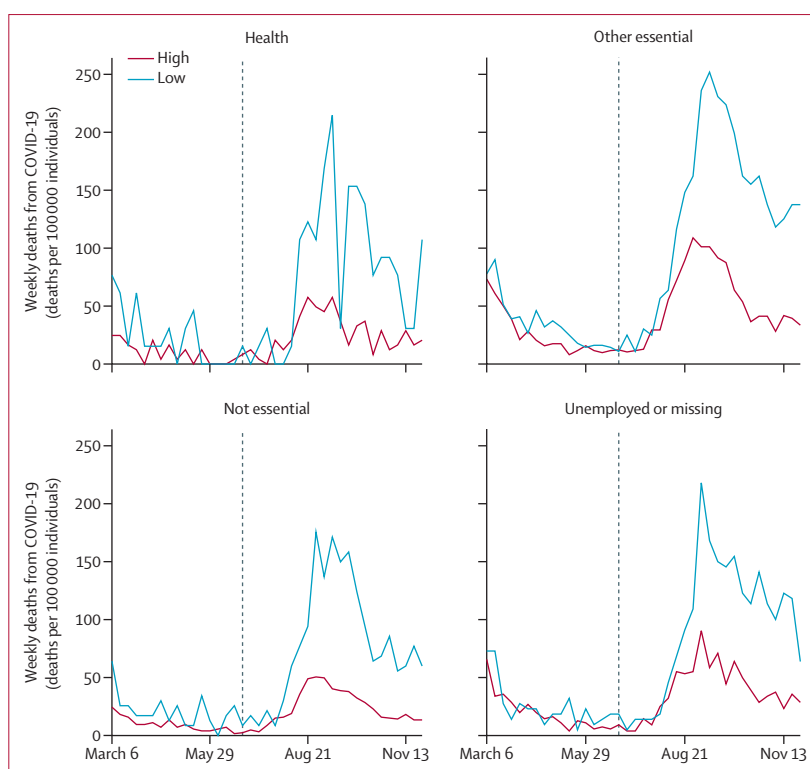
Among the counties included in the vaccine-stratified analysis, 4409 (58.0%) of the total 7592 COVID-19 deaths were in high-uptake counties (after vaccines became available) and 3183 (42.0%) of COVID-19 deaths were in low-uptake counties. Per-capita COVID-19 mortality was 30.0 per 100 000 people in high-uptake counties and 75.0 per 100 000 people in low-uptake counties. In phase 3, per-capita COVID-19 mortality was similar between counties that subsequently had low and high vaccine uptake, regardless of the occupational sector (figure 2). However, COVID-19 mortality in low and high vaccination regions diverged during the surge in phase 4. Among workers in essential sectors other than health workers, the difference in annualised per-capita COVID-19 mortality between high-uptake and low-uptake regions was 9.6 per 100 000 people in phase 3 and 78.8 per 100 000 individuals in phase 4. In sensitivity analyses of our definition of low-uptake and high-uptake vaccine regions, we obtained similar results to the vaccine-stratified analysis, with no meaningful differences (appendix p 3). Although this dichotomy involved a poorer balance between the two groups (as measured via the number of counties represented and geographical representation) than in the main analysis, it prioritised consistency of the definition and higher uptake. For example, the sensitivity analysis excluded several counties from the high-uptake group that did not

reach 65% uptake by Nov 30, 2021: Nevada (60·4% uptake), El Dorado (62·0% uptake), San Diego (62·2% uptake), and Humboldt (63·1% uptake). The sensitivity analysis definition also excluded several counties from the high-uptake group that did not reach 50% uptake until July 12, 2021, or later: Fresno (July 12, 2021), Nevada (July 21, 2021), Colusa (July 21, 2021), and San Diego (July 27, 2021). All of the counties in the high-uptake group under the sensitivity analysis reached 50% uptake by May 28, 2021.

In the sensitivity analysis stratified by age group or by sex, we found higher per-capita COVID-19 mortality among workers in essential sectors than among workers in non-essential sectors. For example, among individuals aged 18–35 years, annualised per-capita COVID-19 mortality was highest among workers in the emergency (15·4 per 100 000 individuals), transportation or logistics (13·0 per 100 000), and manufacturing (11·4 per 100 000) sectors, and lowest among workers in non-essential sectors (3·6 per 100 000). Similarly, among individuals aged 56–65 years, per-capita COVID-19 mortality was highest among workers in the agriculture (468·1 per 100 000), transportation or logistics (330·4 per 100 000), and manufacturing (327·3 per 100 000) sectors, and lowest among workers in non-essential sectors (85·2 per 100 000). Among female workers, per-capita COVID-19 mortality was highest in the agriculture (60·4 per 100 000), manufacturing (54·2 per 100 000), and emergency (48·1 per 100 000) sectors, and lowest in non-essential sectors (21·3 per 100 000). Among male workers, per-capita COVID-19 mortality was highest in the agriculture (168·4 per 100 000), manufacturing (124·7 per 100 000), and transportation or logistics (123·4 per 100 000) sectors, and lowest in non-essential sectors (34·1 per 100 000). The full results by sex are provided in the appendix (p 4).

## Discussion

This comprehensive analysis of COVID-19 and excess mortality by occupational sector in California from March 1, 2020, to Nov 27, 2021, yields three important sets of findings. First, despite vaccine prioritisation for workers in essential sectors, these workers continued to have high COVID-19 mortality during the period of widely available vaccines (March 6 to Nov 27, 2021) and absolute disparities between workers in essential sectors and workers in non-essential sectors increased within the vaccine era during phase 4. Second, relative disparities in COVID-19 mortality between workers in essential sectors and workers in non-essential sectors have mostly declined over time. However, relative disparities between the emergency sector and workers in non-essential sectors increased when vaccines became available and the emergency sector was the essential sector with the highest per-capita COVID-19 mortality. Among workers in essential sectors, per-capita COVID-19 mortality was higher among residents in low-vaccine



**Figure 2** Per-capita COVID-19 mortality among individuals aged 18–65 years living in California, by occupational sector and regions of low or high vaccine uptake, March 6 to Nov 27, 2021. Data are annualised. The vertical dashed line distinguishes phase 3 from phase 4.

uptake counties than those in high-uptake regions, particularly during phase 4.

In this study, per-capita COVID-19 mortality was 2·2 times higher among emergency workers than among health workers during phase 2; this mortality ratio grew to 3·0 during phase 4. Although other explanations are possible (eg, differences in mask wearing), we hypothesise that this widened disparity between emergency and health workers during March 6 to Nov 27, 2021, partly reflects the low levels of vaccine uptake among emergency workers and high levels of vaccine uptake among health workers. In Los Angeles, the state's most populous city, 52% of police officers and 51% of firefighters had received at least one vaccine dose by June 19, 2021.<sup>13</sup> In comparison, 77% of health workers across 350 state hospitals had received at least one vaccine dose by July 23, 2021; vaccine mandates are believed to be a contributing factor to the high uptake.<sup>14</sup> Our study suggests that vaccination might be particularly crucial for preventing deaths during surge periods. During the June 27 to Nov 27, 2021 surge, the peak per-capita COVID-19 mortality among workers in essential non-health sectors was 251·6 per 100 000 individuals in low-uptake regions and 108·6 per 100 000 individuals in high-uptake regions, corresponding to a relative disparity of 2·3.

Protecting workers whose jobs are essential to crucial functions and infrastructure should be a priority in the

pandemic response. However, deaths among workers in essential sectors were still high in our study. Several essential sectors have consistently ranked high in per-capita COVID-19 mortality, including during vaccine availability. These sectors include agriculture, transportation or logistics, facilities, and manufacturing. Although vaccine prioritisation for workers in essential sectors has been effective in prolonging lives (as suggested in our analysis stratifying by regions of low of high vaccine uptake) and might help explain the declines in relative disparities, additional efforts to improve vaccine coverage need to be made. Efforts to increase vaccine uptake among workforces via mandates have been perceived as effective,<sup>15,16</sup> but have faced legal challenges. For example, the US Supreme Court has ruled against the Occupational Safety and Health Administration's emergency temporary standard to require vaccination or testing in workplace settings with at least 100 employees (regardless of the occupational sector).<sup>17,18</sup> In Los Angeles, groups of police officers and firefighters have filed lawsuits in opposition to the city's vaccine mandate.<sup>19</sup>

In the absence of a national mandate, the USA will have to rely on other strategies. These strategies might include local or private vaccine mandates, such as the vaccine mandates at Tyson Foods and United Airlines.<sup>15,20</sup> Community-based or employer-sponsored<sup>21</sup> vaccination efforts can address barriers to vaccine access (eg, transportation and misinformation).<sup>22,23</sup> For example, a coordinated effort, involving the faith community and a mobile clinic, appears to have been effective in improving access and uptake among Black people in San Bernardino County.<sup>24</sup> Policies to increase vaccine uptake can and should address the unique challenges and risks that individuals with low income had during the COVID-19 pandemic,<sup>25</sup> including job security, financial burdens of health care, and disruptions to schooling. For example, paid sick leave can ensure that workers in essential sectors do not have to choose between financial benefits and health risks.<sup>26</sup> Finally, protections against SARS-CoV-2 transmission in workplace settings remain crucial. Given that SARS-CoV-2 can be transmitted via aerosols,<sup>27,28</sup> we urge for free provision of masks, preferably N95 masks or similarly effective masks,<sup>29,30</sup> to workers in essential sectors and improved ventilation in workplace settings.<sup>31</sup>

We acknowledge the limitations of the study. For example, there was possible misclassification of occupation on death certificates by next of kin or the text-to-code system and assignment of occupation codes to sectors was challenging in some cases. An individual classified as having occupation code 5520 (dispatchers) could have been classified as working in emergency services or transportation or logistics sectors. In early work,<sup>1</sup> we attempted to refine our assignment of occupation codes, allowing individuals with the same occupation code to be assigned to different sectors; we

found that this had no discernible impact on the study findings and ultimately abandoned this approach under the principle of methodological parsimony. There were also limitations to our use of the ACS's estimates of population size. The ACS defines residence as current residence rather than usual residence, meaning that migrant workers are included if they are residents at the time of the survey.<sup>32</sup> We also acknowledge that the disparities in COVID-19 mortality in our analysis are not necessarily entirely due to on-the-job risk. However, given the time workers spend in workplaces and the documented weaknesses in COVID-19 protections and various outbreaks in workplaces, these disparities were probably a major contributing factor. Other factors are certainly relevant in understanding the disparities identified in this study. These factors include sex, race, ethnicity (and racism), education, comorbidities, crowded housing, use of public transportation, and health-care access. Our sensitivity analysis stratified by sex showed a larger per-capita COVID-19 mortality among male individuals than among female individuals. This disparity was particularly high among essential sectors and might reflect sex-based sorting of occupation and heterogeneity within sectors. Similarly, Black and Latino people are over-represented among low-wage workers,<sup>33</sup> and low-wage workers also have a higher prevalence of comorbidities than other workers,<sup>34</sup> which are well documented to increase the risk of adverse COVID-19 outcomes.<sup>35</sup> Furthermore, low-wage workers are more likely to live in crowded housing<sup>36</sup> and might be reluctant to take sick leave. Although these factors are important, disparities across occupational sectors persisted in previous work, in which we stratified by race and ethnicity;<sup>1</sup> similarly, in the present study, we continued to observe such disparities in our stratifications by sex and age. Many possible interventions for protecting workers in essential sectors can be pragmatically applied by targeting workers in essential sectors. For example, a worker in an essential sector who becomes infected with SARS-CoV-2 outside of the workplace can be protected via paid sick leave, since this policy can afford the worker time to rest and seek treatment (and, of course, can help prevent workplace transmission). Finally, we acknowledge natural differences across regions with low or high vaccine uptake. These differences include urbanicity, sex, race and ethnicity, educational attainment, and occupation (even within sector). For example, according to the ACS, White individuals make up 65·5% of the population in counties with low vaccine uptake and 57·3% of the population in counties with high vaccine uptake.<sup>37</sup> Such variation might contribute to differences observed in the region-stratified analyses.

More than 1 year after we first reported disparities in COVID-19 mortality across occupational sectors,<sup>1</sup> and even after widespread availability of vaccination, these disparities continue to occur. The patterns are clear: although there have been a large number of COVID-19



deaths among workers in non-essential sectors, workers in essential sectors continue to have the most COVID-19 deaths. However, not all workers in essential sectors have the same increased risk. Health sector workers had lower risk of COVID-19 mortality and excess mortality than workers in several non-health sectors (agriculture, emergency, facilities, manufacturing, and transportation and logistics) both before and after vaccine availability, despite frequent contact with others in many cases. These differences suggest that increased occupational risk of COVID-19 death might not only depend on social contact, but also on workplace safety, worker protections, and worker empowerment (ie, power to negotiate). Furthermore, even in counties with high vaccination rates, essential sectors have increased risks of COVID-19 mortality and excess mortality, suggesting that vaccine uptake alone has been insufficient to erase documented disparities in COVID-19 mortality. We urge for decisive and collaborative action, using a diverse toolkit—including employer mandates for vaccination, paid sick leave, and improved ventilation in workplace settings—to reduce and eliminate disparities across occupational groups.

#### Contributors

ARR and Y-HC did the literature search. Y-HC, ARR, KAD, ACS, MMG, and KB-D designed the study. Y-HC analysed data, created the figures, and wrote the original draft. All authors contributed to interpretation, investigation, and writing (review and editing). Y-HC and RC accessed and verified the underlying data used in the study.

#### Declaration of interests

We declare no competing interests.

#### Data sharing

The data are available via application to the California Department of Public Health.

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