Air quality, health, and economic effects of land use and land cover changes in southeast Asia in the 21st century: a modelling study

Yefu Gu, Tingting Fang*, Yanbin Xu, Xialei Duan, Janice Ser Huay Lee, Wenjun Zhu, Yiwen Zeng, Steve Hung Lam Yim*

Summary

Background Southeast Asia has had substantial land use and land cover changes (LULCCs) in recent decades, affecting air quality, human health, and economic development through biogeophysical and biogeochemical cycles. However, little research has examined the combined effects of different LULCC types and impact pathways comprehensively. We aimed to provide a holistic understanding of how LULCCs across southeast Asia in the 21st century have led to changes in air quality and the consequential effects on human health and the economy.

Methods In this modelling study, we used a regional meteorology–air quality coupled model (WRF–CMAQ) to assess LULCC effects from 2001 to 2018 on the concentrations of surface $PM_{2·5}$ and O_3 through biogeophysical and biogeochemical pathways. The model was configured at a 30×30 km grid size throughout southeast Asia. We used a series of concentration–response models to estimate excess deaths associated with the changes in air pollution concentration caused by LULCCs. The economic implications of these health effects were quantified with age-specific value-of-statistical-life and cost-of-illness approaches.

Findings LULCCs in southeast Asia were associated with 13 000 excess deaths (95% CI 11 000–14 000) in 2018 alone, resulting in US$7·79 billion losses (6·24–9·69). Forest degradation and deforestation was the primary driver, accounting for 29·7% of the burden. Furthermore, more than 60·0% of effects occurred through the biogeophysical pathway.

Interpretation LULCCs in southeast Asia are degrading air quality, causing thousands of excess deaths and billions of dollars in economic losses, with forest degradation and deforestation being the primary driver. The findings emphasise the need for strategic land management to improve environmental conditions and public health, and support sustainable economic development in the area, particularly in the countries most affected, such as Indonesia, Viet Nam, and Thailand.

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Introduction

Southeast Asia is characterised by a range of land use and land cover systems, including expansive tropical rainforests, peatlands, and diverse agricultural areas. In the past 20 years, the equilibrium of these systems has been disrupted by massive forest exploitation, urban sprawl, and other anthropogenic activities.[1] Land use and land cover changes (LULCCs) influence important environmental pathways, including water quality, soil contamination, and exposure to other environmental pollutants, with cascading human health effects.[2,3] Of particular concern is the effect of these changes on air quality: each LULCC type evokes unique responses to the surface flux of energy, water, and air compositions, which, through mutual interaction, impose profound effects on air quality in this densely populated region.[4] Meanwhile, long-term monitoring has revealed a continuous rise of surface $PM_{2·5}$ and O_3 concentrations in southeast Asia, despite the reduction observed in many neighbouring regions.[5,6] Therefore, distinguishing the role of LULCCs from other influencing factors, such as increased anthropogenic emissions and climate variability, in the air quality of southeast Asia is crucial to formulating emission control and land management strategies for air pollution mitigation.

Southeast Asia has had substantial and complex LULCCs. The region is one of the world's major hotspots of forest degradation and deforestation.[7] Large tracts of tropical forest have been replaced by woody plantations to sustain the growing need for cash crops, such as palm oil and rubber.[8] This conversion results in higher latent heat flux and isoprene emissions, which are more favourable for secondary pollutant formation. This change also generates more NO from the application of fertilisers.[9] Furthermore, massive natural forests have been converted to cropland and pastureland, leading to increased O_3 concentration in the region.[10] Drastic urbanisation in southeast Asia is also a cause for concern. The rapid sprawl of built-up areas can increase surface air temperature, promoting temperature and precipitation extremes.[11,12] Changes in urbanisation metrics are strongly correlated with surface-level $PM_{2·5}$

Research in context

Evidence before this study

Southeast Asia has undergone substantial and complex land use and land cover changes in past decades. These modifications can alter regional climate and air composition in the region, posing a profound risk to air quality, but the corresponding effects on human health and economic development remain unknown. We searched the Web of Science Core Collection for literature published between database inception and Nov 1, 2024, with the terms "land use changes", "land cover changes", "$PM_{2·5}$", "ozone", "health impacts", and "economic impacts". We found several studies that explored the meteorological and air quality responses of specific land use and land cover change types, such as urbanisation, deforestation, and cropland expansion. A few studies have also investigated the effects of all land use and land cover changes in an area while focusing on the implications of individual air pollutant species. Findings relating to whether land use and land cover changes improve or deteriorate air quality in the same region were substantially varied, mostly depending on which influencing pathway was considered. No previous study has comprehensively investigated the effects of land use and land cover changes on regional air quality, human health, and economic cost.

Added value of this study

Our results show that land use and land cover change in southeast Asia in the 21st century led to an overall increase in $PM_{2·5}$ and O_3 concentrations, resulting in 13 000 excess deaths and US$7·79 billion in economic losses in 2018 alone. Forest degradation and deforestation, the major driver of these increases, accounted for 29·7% of this burden, while over 60·0% of air quality impacts occurred through biogeophysical pathways. These findings highlight the urgent need for sustainable land management strategies to mitigate environmental degradation, protect public health, and foster economic stability in this rapidly developing region. They also emphasise the importance of localised studies to guide region-specific interventions, addressing diverse effects across different countries.

Implications of all the available evidence

The available evidence highlights that land use and land cover changes in southeast Asia substantially affect air quality, public health, and economic stability. Impacts are substantially varied in different countries: some bear tremendous health and economic burdens that can be close to the impacts resulting from their major emission sectors, whereas others have seen air quality improvements. To mitigate the worsening impacts, policy makers should balance economic development, air quality protection, and public health outcomes by prioritising sustainable land use practices and enforcing stricter regulations for deforestation, especially the expansion of industrial plantations, while promoting afforestation measures. Future studies should focus on further implications of land use and land cover changes on climate variability, considering the long-term interplay between land cover types and complete interactions between land and atmosphere. Research is also needed to project future land cover modifications and their effects on climate and air quality under varying socioeconomic scenarios.

concentration in southeast Asia,[13] suggesting underlying effects of urban expansion on air pollution. Existing studies have focused on the effects of individual LULCC types in southeast Asia. However, their findings remained inconclusive, as the results largely depended on the assumed distribution of pre-existing land use and land cover types.

LULCCs affect regional air quality through a complex physicochemical process. In terms of the biogeochemical cycle, LULCCs alter the availability of emission and uptake sources, directly changing the net flux of air composition. Studies have found that forest loss and cropland expansion in southeast Asia have perturbed the emission rates of biogenic volatile organic compounds and dry deposition velocity, explaining the continuous rise of O_3 and aerosol concentrations observed in the region.[14] LULCCs also influence atmospheric dynamics via the biogeophysical process:[15] it alters surface air exchange of heat and moisture, which is key to the chemical formation and removal of atmospheric components.[16,17] Modifications of some types of LULCCs might change surface roughness, which affect horizontal air movement and air pollutant propagation. Substantial forest degradation and deforestation in southeast Asia has been shown to weaken moisture convergence and reduce precipitation in both local and remote regions.[18] Forest degradation has also modified air temperature through the cooling effects of increased surface albedo and warming effects of reduced evapotranspiration.[19,20] These meteorological variabilities imply potential effects on regional air quality. Previous studies have examined the effects of individual LULCC types or single pathways in southeast Asia. However, capturing the net effects of LULCC requires integrating both biogeochemical and biogeophysical pathways while accounting for complex interactions across all LULCC types, as these processes occur simultaneously in the real world. Breaking down these effect pathways can identify the dominant mechanisms driving LULCC effects, thereby providing policy makers with evidence-based strategies for air pollution mitigation.

This study aimed to provide a holistic understanding of how LULCCs across southeast Asia in the 21st century have led to changes in air quality, and the consequential effects of these changes on human health and the economy.

Methods

Model design

In this modelling study, our analytical approach involved three main components: (1) atmospheric chemistry and

physics modelling with the Weather Research and Forecasting (WRF)–Community Multiscale Air Quality (CMAQ) system to simulate how LULCCs from 2001 to 2018 affected meteorology and air quality (through $PM_{2.5}$ and O_3 concentrations) in southeast Asia; (2) a health impact assessment with concentration–response models to translate air quality changes into premature mortality estimates; and (3) an economic valuation of these health changes through value-of-statistical-life (VSL) and cost-of-illness (COI) methods. We quantified uncertainties in the health impact assessment and economic evaluation through Monte-Carlo simulations. Our workflow is described in figure 1.

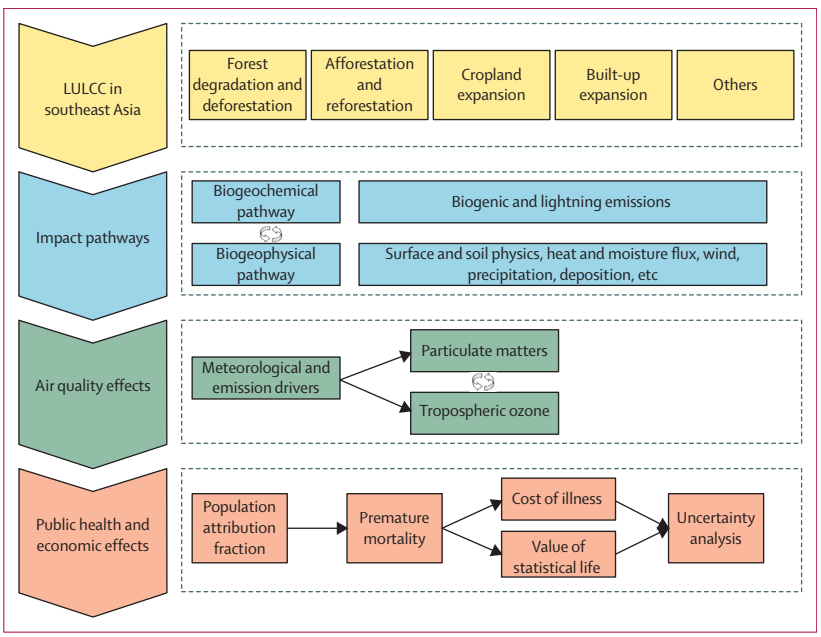


Figure 1: **Conceptual framework of the cascading effects of LULCCs on air quality, public health, and economic outcomes**
LULCC=land use and land cover change.

WRF–CMAQ model

We adapted the WRF–CMAQ model to investigate changes in surface-level $PM_{2.5}$ and O_3 concentrations in response to LULCCs in southeast Asia. We used the WRF (version 3.8) to perform the dynamics of meteorological conditions that drive the CMAQ (version 5.3) simulation of the chemistry transport of trace species. A multiscenario comparison was incorporated to isolate the effects of LULCCs and their effect pathways. Each scenario consisted of a 1-year WRF–CMAQ simulation, with simulations during December to February; March to May; June to August; and September to November. The WRF–CMAQ model was configured at a 30×30 km grid size domain, covering the whole of southeast Asia, the southern part of east Asia, and the eastern part of south Asia (appendix p 18). 26 layers were set in the model to describe the vertical distributions of atmospheric components and meteorological variables from surface level to the lower stratosphere. Land data for this model were updated with datasets from 2001 and 2018, including high-resolution land use and land cover, urban morphology, and vegetation cover data, to account for the effects of long-term LULCCs. The years 2001 and 2018 were chosen because they encompass the most drastic LULCCs in the region, and the relevant land cover details can be obtained from satellite-retrieved products.[21] Detailed compiled land data and results are described in the appendix (pp 3–4 and pp 12–14). The WRF–CMAQ model specifications are detailed in the appendix (pp 4–6).

The WRF–CMAQ simulations were validated against ground-level observations from air quality monitoring stations across southeast Asia. The evaluation method, statistical metrics, and results of this validation are detailed in the appendix (p 12).

Scenario design

We designed a series of simulation scenarios to isolate the effect of LULCCs and their effect pathways on air quality. The baseline scenario (lc18) was introduced, in which all model inputs were controlled for 2018. The lc01 scenario was modified from lc18 by replacing the WRF–CMAQ land cover information with data for 2001. Subtracting lc01 from lc18 yielded the total effects of LULCCs from 2001 to 2018. The lc01-bgp and lc01-bgc scenarios were developed for the WRF–CMAQ simulation to reveal the different pathways through which LULCCs could affect meteorology and air quality. Scenario lc01-bgp incorporated 2018 land cover information for the WRF simulation while retaining all other settings implemented in lc01. The (originally online) calculated emission inventories were extracted from the emission diagnostic output of lc01 and recompiled as offline inventories to maintain consistency in emission input. Conversely, lc01-bgc kept the biogeophysical pathway from 2018 with WRF land use information from lc01 but emission inventories and CMAQ land cover information from lc18. Subtracting lc01 from lc01-bgp yielded LULCC effects via biogeophysical pathways, and subtracting lc01 from lc01-bgc yielded biogeochemical pathway effects.

To evaluate the sensitivity of LULCC effects, we put each scenario through nine repeated simulations, with the initial time of each simulation slightly perturbed. The significance of the model estimates was determined with Student's *t* test.

See Online for appendix

Health impact assessment

We used the population attributable fraction, incident rate, and size of the exposed population to estimate excess deaths associated with exposure to ambient $PM_{2.5}$ and O_3 concentrations under varying land use and land cover conditions in 2001 and 2018. The population attributable fraction was calculated with a series of concentration–response models that estimated the relative risk of cause-specific premature mortality attributable to excessive air pollution exposure compared with clean conditions.

Specifically, the relative risk of excessive $PM_{2·5}$ exposure was estimated by the Global Exposure Mortality Model,[22] which specifies the mortality risk due to non-communicable diseases (including ischaemic heart disease, stroke, chronic obstructive pulmonary disease, and lung cancer) and lower respiratory infections by 12 age groups from age 25 years to older than 80 years in 5-year intervals. Relative risk of all-cause mortality because of ozone exposure was resolved by a log-linear model.[23] Model coefficients were derived from the Cox proportional hazards regression fitted to data from the Cancer Prevention Study II.[24] The formulas for the premature mortality estimation, concentration–response models, population attributable fraction, and the required data are detailed in the appendix (pp 6–8).

Health effects in each country were further attributed to dominant LULCC types through a linear decomposition approach. For each grid cell, we calculated the fractional area change for each LULCC type (eg, fraction of the cell converted from forest to woody savanna) and assumed that the health effect at that location was proportionally distributed among the LULCC types based on their relative area changes. Country-level attributions were then calculated by summing the spatially attributed effects across all grid cells within each country.

Economic cost estimation

The economic costs associated with the health effects of LULCCs in southeast Asian countries were quantified with age-specific VSL, a widely adopted measure to comprehensively evaluate the health cost of excess deaths attributable to air pollution.[25] We also used the COI method to estimate the expenditure related to LULCCs on health care and productivity loss. The detailed calculations and data sources for health-care expenditure, productivity loss, and VSL are provided in the appendix (pp 8–11).

Statistical analysis

The spatial heterogeneity of the WRF–CMAQ model performance and the randomness of the coefficients and inputs within the concentration–response models and health-care expenditure, productivity loss, and VSL estimation models were expected to accumulate, affecting the accuracy of the health impact and economic cost estimates. We used the Monte-Carlo approach to integrate the randomness of these variables, reconstructed by the median, 2·5th percentile, and 97·5th percentile (assuming triangular distributions). This distribution has been widely used in health impact and uncertainty assessments. Health impact and economic cost estimation models were run 2000 times, each randomly drawing unique model coefficients, inputs, and the normalised mean bias of WRF–CMAQ used to assimilate the simulated $PM_{2·5}$ and O_3 concentrations. The results were reported as the median value and 95% CIs of the output distributions in the health impact and economic cost simulations.

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

Figure 2A indicates that LULCCs generally elevated the annual mean surface maximum daily 8-h average O_3 concentration by up to 15·8 parts per billion. The increase was particularly large in maritime southeast Asia, such as the southern Malay Peninsula, Sumatra, and the coastal region of Borneo, where forest degradation and deforestation reduced O_3 deposition during the daytime (appendix p 22). In continental southeast Asia, the annual mean maximum daily 8-h average O_3 concentration increased by only 0·16 parts per billion, exhibiting substantial regional variability because of complex LULCC types (appendix p 22). Surface O_3 concentrations increased in the regions with major forest degradation and deforestation, such as Laos, Cambodia, northern Thailand, and Viet Nam, but decreased in central Myanmar, eastern Thailand, and eastern Viet Nam, where O_3 dry deposition was accelerated by cropland expansion and afforestation and reforestation (appendix p 22). Therefore, the main pathway for O_3 changes was through biogeophysical processes, accounting for an estimated 75·1% of mean maximum daily 8-h average O_3 increase in southeast Asia overall, including 73·4% in maritime southeast Asia and 70·4% in continental southeast Asia, especially during wetter seasons (ie, December, January, and February in maritime southeast Asia and March, April, and May in continental southeast Asia; figure 2C, D).

Compared with O_3, the LULCC-induced surface $PM_{2·5}$ concentration increase was more homogeneous across southeast Asia (figure 2B). This enhancement was more pronounced in continental southeast Asia, where surface cooling caused by afforestation and reforestation and cropland expansion promoted night-time aerosol formation (appendix p 22). In maritime southeast Asia, large-scale forest degradation and deforestation with a low dry deposition rate also favoured $PM_{2·5}$ accumulation (appendix p 22). Metropolises including Jakarta (Indonesia) and Ho Chi Minh City (Viet Nam) were exceptions, where the surface $PM_{2·5}$ concentration declined by up to 5·13 $\mu g/m^3$. Substantial built-up expansion weakened radiative cooling during the evening transition period (1700 h to 1900 h), reducing aerosol formation in these cities (appendix p 22). Likewise, the biogeophysical pathway was the major pathway for $PM_{2·5}$ changes, accounting for 64·5% of the overall increase in southeast Asia, including 50·1% in maritime southeast Asia and 77·6% in continental southeast Asia, especially during the warmer seasons (ie, June, July, and August in maritime southeast Asia and March, April, and May in continental southeast Asia; figure 2E, F).

We estimated that changes in $PM_{2·5}$ and O_3 exposure because of LULCCs were associated with an increase of 13 000 (95% CI 11 000–14 000) excess deaths in southeast

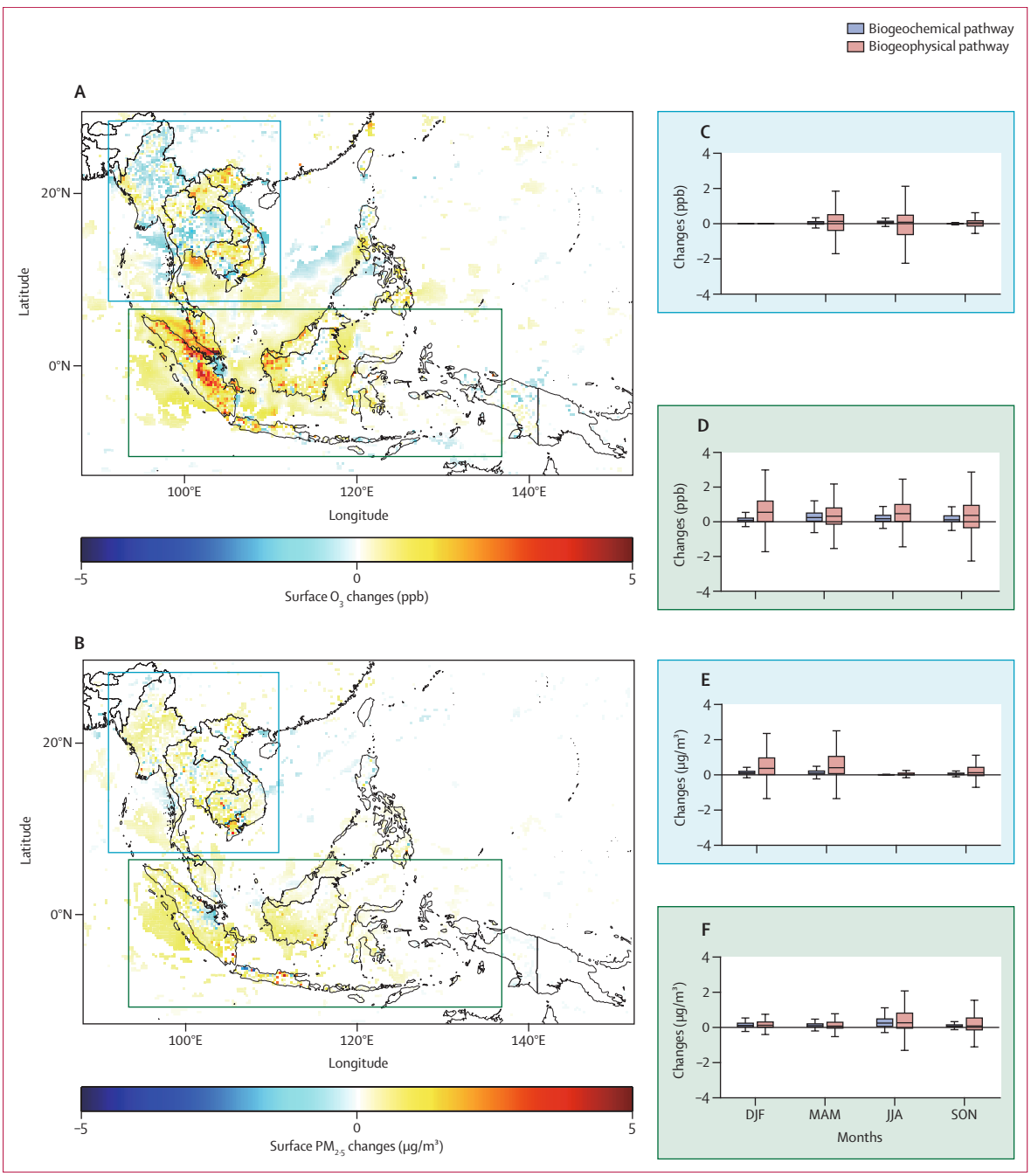


Figure 2: **Effects of LULCCs in the 2001–18 period on the surface-level mean maximum daily 8-h average of O_3 and mean $PM_{2·5}$ concentrations in southeast Asia**
Spatial distribution of annual mean effects of LULCCs on surface O_3 (A) or surface $PM_{2·5}$ (B), or averaged effects across month groups on surface O_3 in continental southeast Asia (C) and maritime southeast Asia (D), or on surface $PM_{2·5}$ in continental southeast Asia (E) and maritime southeast Asia (F). Only robust results that were significant in a Student's *t* test ($p<0·05$) are shown. DJF=December, January, and February. JJA=June, July, and August. LULCC=land use and land cover change. MAM=March, April, and May. ppb=parts per billion. SON=September, October, and November.

Asian countries in 2018 alone. Major health effects occurred in Java (Indonesia), the Mekong River Delta (Viet Nam), and the Red River Delta (Viet Nam; figure 3). Conversely, LULCCs also improved public health in Jakarta and parts of continental southeast Asia due to reductions in O_3 or $PM_{2·5}$ concentrations.

Excess deaths increased in almost all southeast Asian countries, with the largest increase observed in Indonesia with 4800 (95% CI 3900–5800), Viet Nam with 2800 (2500–3100), and Thailand with 1800 (1700–2000) deaths. These countries were also among those with the largest increase in mortality rates (appendix p 25). This finding

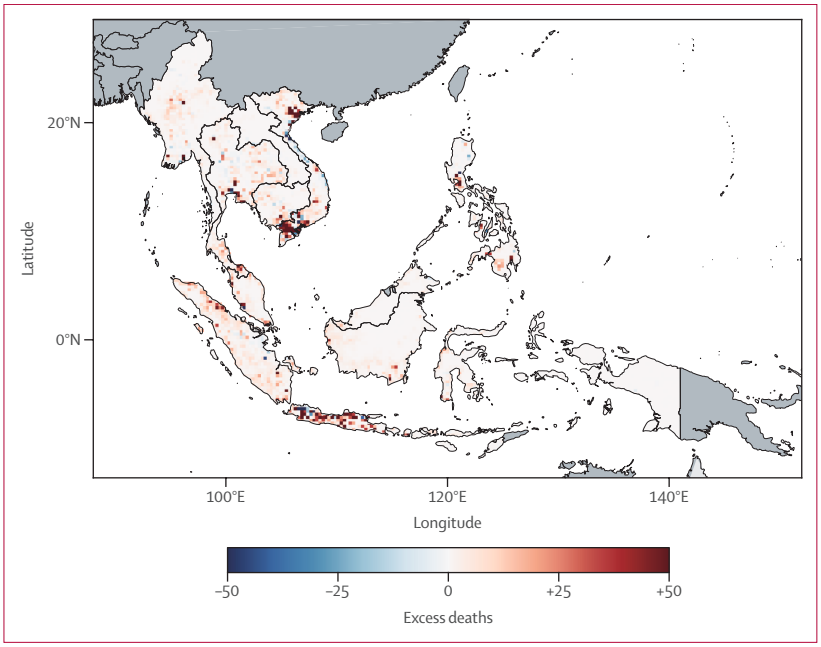


Figure 3: **Annual $PM_{2·5}$-related and O_3-related excess deaths due to LULCCs in the 2001–18 period in southeast Asia**
Only robust results that were statistically significant in the Student's *t* test ($p<0·05$) are shown. LULCC=land use and land cover change.

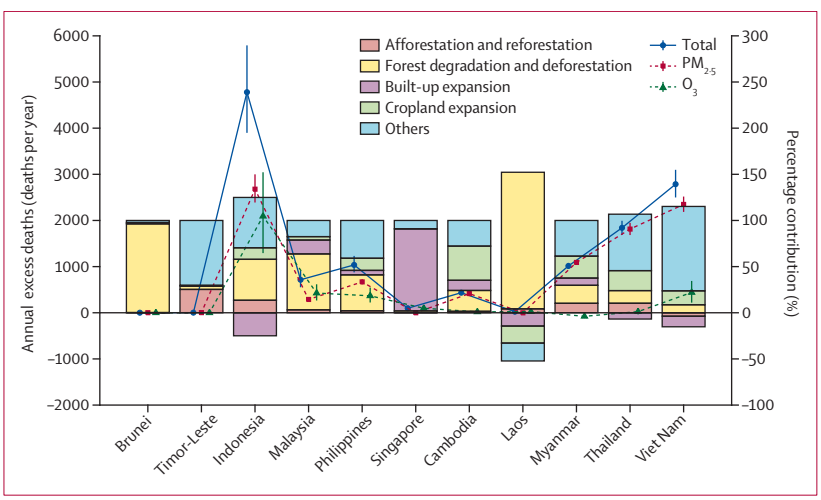


Figure 4: **Changes in annual $PM_{2·5}$-related and O_3-related excess deaths across different LULCC types**
Line charts show the total excess deaths and the breakdown of $PM_{2·5}$-related and O_3-related exposure, with reference to the left y-axis. Stacked bar charts depict the percentage contribution of dominant LULCC types, with reference to the right y-axis. The excess deaths because of four dominant LULCC types are shown with all other types grouped together. Only robust results that were statistically significant in the Student's *t* test ($p<0·05$) are shown. LULCC=land use and land cover change.

suggests that health effects in different countries were mainly because of changes in air pollution caused by LULCCs, rather than population sizes. Conversely, country-level changes in excess deaths were dominated by different causes. Excess death increases in maritime southeast Asian countries, including Malaysia, the Philippines, and Singapore, were mainly attributed to increases in O_3 exposure. In contrast, $PM_{2·5}$ concentration changes were associated with excess deaths in continental southeast Asian countries, including Viet Nam, Thailand, and Myanmar. The complete excess deaths and mortality rate data for each country are detailed in the appendix (p 25).

The results of the linear decomposition approach to attributing health effects to four dominant LULCC types are described in the bar chart in figure 4. Four major types of LULCCs (forest degradation and deforestation, afforestation and reforestation, cropland expansion, and built-up expansion) were associated with approximately 5400 (95% CI 4200–6700) excess deaths in 2018 alone. Making up 39·8% (appendix p 12) of total LULCCs, forest degradation and deforestation accounted for 29·7% of the effects, reaching the largest proportion in Laos (148·0%), Brunei (96·2%), and Malaysia (60·6%). Cropland expansion contributed to 15·5% of total excess death increases, with the leading contribution in Cambodia (37·1%), Myanmar (23·8%), and Thailand (21·7%). Afforestation and reforestation only accounted for 7·0% of increases in total excess death. Nevertheless, this land cover conversion made up a large portion of excess death variation in Timor-Leste (25·3%), Indonesia (13·5%), Thailand (10·3%), and Myanmar (10·2%). Built-up expansion was the only major LULCC type that improved overall public health, averting 10·0% of excess deaths because of LULCCs in southeast Asia. Indonesia and Laos had the largest public health benefit from built-up expansion, accounting for up to 25·0% of total LULCC effects.

To contextualise the importance of these LULCC effects, we compared the health impact estimates with those from major emission sources in southeast Asia. LULCC-induced health effects represented approximately 9·0% increases of the total air pollution-related excess deaths during the same period.[26] Based on our previous source apportionment study,[27] the LULCC-induced health impacts estimated in this study were also similar to the contributions of major emission sectors, such as biomass burning (~24 000 deaths [95% CI 10 000–40 000] in 2018; appendix p 28) and biogenic emissions (~37 000 deaths [17 000–62 000] in 2018; appendix p 28). For less populated countries, such as Singapore, O_3-related excess deaths from LULCCs (~98 deaths [61–141] in 2018; appendix p 25) were equivalent to 81·7% of the effects from local emissions (~120 deaths [68–200] in 2018; appendix p 27), larger than the individual effects of any emission sector.[27] In contrast, populous countries such as Indonesia had smaller health impacts from LULCCs than from ambient air pollution exposure (~374 000 deaths [168 000–615 000] in 2018; appendix p 27).[27]

The excess deaths in 2018 alone due to LULCC-related changes in air pollution resulted in US$7·79 billion (95% CI 6·24–9·69) in economic costs in southeast Asia, accounting for 0·09% of the annual gross domestic product (GDP) in this region (table). The economic effects were the largest in Indonesia at $2·58 billion (95% CI 2·00–3·31) and Thailand at $2·20 billion (1·87–2·55). This is equivalent to

	VSL, million US$	COI, million US$		VSL as % of GDP (×100)	COI as % of CHE (×10)
		Productivity loss	Health-care costs		
Brunei	6 (5 to 6)	0 (0 to 0)	0 (0 to 0)	1·6%	1·4%
Timor-Leste	0 (0 to 1)	0 (0 to 0)	0 (0 to 0)	0·7%	0·7%
Indonesia	2580 (2007 to 3312)	391 (358 to 424)	13·1 (11·5 to 14·8)	7·8%	13·5%
Malaysia	784 (641 to 950)	76 (67 to 85)	3·4 (2·8 to 4·2)	7·8%	5·9%
Philippines	192 (138 to 262)	20 (17 to 22)	1·1 (0·9 to 1·3)	1·9%	1·5%
Singapore	729 (571 to 905)	65 (59 to 70)	2·8 (2·2 to 3·4)	11·0%	4·4%
Cambodia	56 (38 to 81)	10 (10 to 11)	0·4 (0·3 to 0·4)	7·7%	7·3%
Laos	–2 (–4 to 0)	–1 (–1 to –1)	0 (0 to 0)	–0·3%	–1·8%
Myanmar	171 (123 to 243)	41 (38 to 43)	1 (0·9 to 1)	5·3%	13·1%
Thailand	2202 (1874 to 2554)	301 (279 to 323)	7·3 (7 to 7·7)	14·8%	15·7%
Viet Nam	1076 (850 to 1377)	163 (152 to 174)	5·2 (4·9 to 5·6)	10·2%	10·8%
Southeast Asia	7794 (6244 to 9690)	1066 (979 to 1153)	34 (31 to 39)	8·7%	9·7%

Data are median (95% CI), unless stated otherwise. Million US$ is according to 2018 rates, adjusted for purchasing power parity in 2021. CHE=current health-care expenditure. COI=cost of illness. GDP=gross domestic product. VSL=value of statistical life.

Table: **Economic costs because of the changes in annual excess deaths attributable to land use and land cover changes over 2001–18 period in southeast Asian countries**

around a 0·1% decrease in the GDP of these two countries (table). Besides the induced excess deaths, a higher per-capita GDP in these two countries than in the other included countries was another reason for the large economic effect, suggesting greater affordability of avoiding premature mortality. Laos had a decline in excess deaths from LULCCs, avoiding economic loss from air pollution. In particular, the relatively small number of excess death changes in Singapore corresponded to $0·73 billion (0·57–0·91) lost, amounting to 0·1% of its 2018 GDP. This substantial economic cost was associated with its developed economy and consequential VSL.

Apart from the total economic cost, LULCCs also imposed a substantial burden on health-care programmes in different southeast Asian countries, as estimated by the COI method. LULCCs were estimated to cause a health-care cost of $1·10 billion (1·01–1·19), including productivity losses of $1·07 billion (95% CI 0·98–1·15) and medical costs of $0·03 billion (0·03–0·04), which are together equivalent to 1·0% of health-care expenditure in southeast Asia in 2018. Indonesia and Thailand had the leading increases of COI at $0·40 billion (0·37–0·44) in Indonesia and $0·31 billion (0·29–0·33) in Thailand. Myanmar and Viet Nam also had substantial contributions from COI increases to their health-care expenditure (1·3% in Myanmar and 1·1% in Viet Nam).

Discussion

Our analysis shows that LULCCs between 2001 and 2018 led to an increase in the overall $PM_{2·5}$ and O_3 concentrations in southeast Asia, resulting in a total of 13 000 (95% CI 11 000–14 000) annual excess deaths in 2018. These deaths were predominantly linked to forest degradation and deforestation. Indonesia had the largest increase in excess deaths with 4800 deaths (3900–5800), followed by Viet Nam and Thailand.

The decreased $PM_{2·5}$ concentration from built-up expansion in Java was shown to improve public health and partly offset the adverse effects of forest degradation and deforestation as well as cropland expansion elsewhere in the country. A growing number of studies have identified increasing surface-level $PM_{2·5}$ and O_3 concentrations in southeast Asia in the past few decades.[5,6] These trends have been largely attributed to intensifying anthropogenic emissions and biomass burning.[28] Our study elucidates the important role of LULCCs in the accumulation of air pollutants, partly accounting for the continuously deteriorating air quality in southeast Asia. Distinctive effects in southeast Asian countries and inequity issues also deserve consideration by local governments when evaluating their air pollution mitigation and development policies.

The economic implications of LULCC reported in this study are profound. Our analysis revealed that LULCC-induced health impacts in 2018 alone resulted in an estimated total economic cost of $7·79 billion (95% CI 6·24–9·69) and a health-care burden of $1·10 billion (1·01–1·19) in 2018. Indonesia and Thailand received the largest economic burdens, which are equivalent to 0·1% of their respective GDP and up to 1·6% of their health-care expenditure. The high costs in these countries were attributed not only to increased mortality rates but also to their relatively high GDPs and the associated health-care expenses and VSL. This finding highlights the complex interplay between urban development and air quality management. The productivity losses measure future lifetime income lost because of premature death, indicating the creation of long-term economic burdens for future generations who have no role in current land use decisions. These intergenerational impacts of LULCCs also warrant attention.

Forest degradation and deforestation was the major drivers (making up 39·8%; appendix p 12) of total LULCCs

in southeast Asia, mostly because of the rapid expansion of plantations. Our estimation indicates that forest degradation and deforestation was the leading contributors to the perturbations in the surface energy balance and moisture convection. It also induced the largest surface-level $PM_{2·5}$ and O_3 concentration increases, causing 29·7% of the total LULCC-induced health impacts and economic losses in the region. With the increasing demand for rubber and palm oil, the increasing need for planting area and subsequent forest degradation and deforestation are likely to lead to further substantial effects on regional climate and air quality. Afforestation and reforestation contributed 7·0% of changes in excess deaths, whereas cropland expansion made a larger contribution of 15·5%, both through surface cooling and nocturnal aerosol formation. We noticed that afforestation and reforestation and forest degradation and deforestation, through different mechanisms, both led to an overall increase in excess deaths and economic costs. These findings underscore the need for coordinated land cover management and anthropogenic emission control strategies to achieve effective air quality and public health improvement. Future greening initiatives should prioritise plant species selection based on biogenic emission profiles to prevent unintended increases in air pollution.

Our results show that more than 60·0% of the effects occurred through the biogeophysical pathway. In particular, changes in surface and aerodynamic resistance affected the dry deposition velocity of gaseous and aerosol species, which predominated the LULCC effects on $PM_{2·5}$ and O_3 concentrations. Effects via the biogeochemical pathway were less severe. We found that major LULCC types, including forest degradation and deforestation, afforestation and reforestation, and cropland expansion, did not substantially interfere with the photochemical production of O_3 or secondary aerosol formation. Integrating the meteorological response and considering the complex interaction of surface–air exchange of energy and moisture are therefore crucial when comprehensively evaluating the LULCC effects on atmospheric composition.

Several limitations due to data availability should be considered when interpreting our findings. First, our analysis quantified the health and economic effects of cumulative LULCCs from 2001 to 2018 based solely on 2018 exposure and population conditions, representing a conservative estimate. The progressive LULCCs over this period would have caused excess deaths in each intervening year. Many LULCC types, such as forest degradation and deforestation, are effectively irreversible on a human timescale, and therefore the associated air quality degradation and health burdens will persist well beyond 2018. Second, concentration–response functions were derived from North American, European, and east Asian cohorts, as long-term epidemiological studies specifically in southeast Asian populations are scarce. These data sources potentially introduced uncertainty for southeast Asian populations with different baseline susceptibilities. Third, economic valuation relies on VSL transfer from countries in the Organisation for Economic Co-operation and Development with adjustments for income elasticity and other factors. This method involves assumptions about willingness-to-pay scaling across economic contexts and raises ethical considerations regarding differential life valuation. Nevertheless, the COI method included in this study provides an alternative, more conservative economic estimate based on actual expenditures, representing a lower bound of the true economic burden. Finally, we focused exclusively on $PM_{2·5}$-related and O_3-related effects on excess deaths. Other health endpoints, such as morbidity, hospital admissions, and their economic effects, were not considered because the required data for these estimations are not available for most countries in southeast Asia. Future research would benefit substantially from the development of epidemiological and economic studies in southeast Asia.

In summary, our study provides a comprehensive assessment of how LULCCs in southeast Asia in the 21st century have degraded air quality, resulting in thousands of excess deaths and billions of dollars in economic losses. Forest degradation and deforestation was identified as the primary driver, and the biogeophysical pathway was the dominant mechanism. These source and pathway decomposition findings provide an evidence base for land management strategies beyond conventional climate-focused frameworks. Specifically, the estimated health and economic co-benefits from avoided deforestation strengthen the case for forest conservation under transnational initiatives such as Reducing Emissions from Deforestation and Forest Degradation, in which air quality and public health dimensions should be incorporated into accounting and decision-making frameworks. More broadly, our findings inform progress towards multiple Sustainable Development Goals (SDGs), particularly SDG 3 (Good Health and Well-being) and SDG 15 (Life on Land). As rapid land cover transformations in southeast Asia continue, integrating comprehensive air quality, health, and economic impact assessments into land use planning and cross-border environmental governance will be essential to safeguarding public health and achieving sustainable development across the region.

Contributors

YG: data curation, formal analysis, investigation, methodology, software configuration and execution, supervision, validation, visualisation, and writing of the original draft. TF: data curation, formal analysis, investigation, methodology, software configuration and execution, supervision, validation, visualisation, and writing of the original draft. YX: review and editing. XD: validation and review and editing. JSHL: review and editing. WZ: validation and review and editing. YZ: review and editing. SHLY: conceptualisation, formal analysis, funding acquisition, investigation, methodology, project administration, resources acquisition, supervision, validation, and review and editing. All authors had access to the data in this study and had final responsibility for the decision to submit for publication. YG and SHLY have accessed and verified the underlying data.

Declaration of interests

We declare no competing interests.

Data sharing

Our estimates rely on multiple datasets, including health, economic, demographic, and land data. These datasets are available online and detailed in the appendix (pp 3–11). $PM_{2.5}$ and O_3 concentration changes caused by LULCCs simulated in the WRF–CMAQ model are available from the corresponding author on request.

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