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RESEARCH ARTICLE

A microsimulation model of smoking prevalence in England: exploring potential impacts of 'Tobacco 21' and e-cigarette policy scenarios on socioeconomic and regional inequalities

[version 1; peer review: awaiting peer review]

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Abstract

Background

The burden of morbidity and mortality in England, is greater among priority groups such as those with lower income or routine and manual occupations. Using a microsimulation model, we estimate projected changes in smoking prevalence according to socio-economic position under selected policy scenarios that are relevant to ongoing policy implementation and debate.

Methods

Initiated using real-world data from adult (16+) respondents to the Smoking Toolkit Study (STS), the 'QuitSimX' microsimulation model projects individual-level smoking uptake and cessation in England over time. The simulation was run under two separate policy scenarios, raising the age of sale of tobacco products to 21 (simulations run from 2013–2023), and moving a proportion of all individuals quitting using a certain method (such as over the counter nicotine replacement therapy), or no method, to using e-cigarettes instead (simulations run from 2015–2025). Under each scenario, the size of effect were specified, and the outcomes simulated and assessed by indicators of socio-economic position. Absolute and relative inequalities were examined by comparing at the initial and

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final timepoint the i) absolute difference in smoking prevalence between less and more advantaged groups subgroups and ii) the ratio of smoking prevalence.

Results

While absolute and relative inequalities in smoking prevalence declined across the simulated period under all policy scenarios and the counterfactual 'no intervention' scenario, at the final time point absolute and relative inequalities between social grades and regions were similar across all scenarios, with the exception that the relative (but not absolute) inequality under the most impactful tobacco 21 scenario as marginally higher than under the baseline scenario.

Conclusion

A microsimulation model of smoking in England illustrates that absolute inequalities are projected to decrease under a Tobacco 21 or quitting with e-cigarettes scenario but that some policy solutions (Tobacco 21) may result in an increase in relative inequalities.

Plain Language Summary

This study used a computer simulation model of smoking uptake and quitting smoking to predict how different tobacco policies might affect smoking rates in England, especially among lower-income groups. Based on data from a large national survey of smoking in England, we looked at two scenarios: raising the legal smoking age to 21 and encouraging more people to use e-cigarettes when trying to quit. We found that both policies would likely reduce overall smoking rates across different socioeconomic groups. However, raising the smoking age to 21 might slightly increase the relative difference in smoking rates between those from less advantaged and more advantage socioeconomic groups, even though the absolute difference would still decrease. In conclusion raising the age of sale to 21, and encouraging switching from cigarette smoking to e-cigarette use policies could help reduce smoking overall, and policymakers should be aware that some approaches might have different effects on absolute versus relative inequalities.

Keywords

Simulation, smoking, vaping, policy

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Background

Recent declines in smoking in many high income countries likely reflect a combination of tobacco control policies (taxation, smoke-free policies, mass media campaigns, display bans) and in certain countries, such as the United Kingdom, also emergent technologies such as electronic cigarettes (e-cigarettes) acting across the population[1–5]. Accelerating this decline, while also narrowing the persistent socioeconomic inequalities in smoking[6], will require ambitious interventions and policies to both increase smoking cessation and reduce smoking uptake. To this end, the UK government recently initiated the first steps of a process to sign into law a 'smokefree generation' policy - where anyone born on or after 1 January 2009 will never legally be able to be sold tobacco[7,8] – and announced plans to provide an e-cigarette to one in five people who smoke in England[8]. While it is hoped that these policies will accelerate reductions in smoking prevalence, it is not clear how they will affect existing inequalities in smoking. Without evidence from other countries, and given experimental studies are not feasible, computational tools can be used to estimate the potential impact of interventions and policies on smoking in the population. Using a microsimulation model, this study presents potential socioeconomic and regional smoking prevalence outcomes under two hypothetical policy scenarios related to raising the age of sale, and increasing e-cigarette use in England.

Systems science methods are increasingly used by researchers and policymakers who recognise that population health is a complex system involving dynamic interactions between individuals, communities, institutions and other entities at different levels in society[9]. One computational systems approach is microsimulation; a model that simulates individual 'agents' in a population. In the population health context, a microsimulation model seeks to understand how individual agent characteristics relevant to a given disease or behaviour (e.g., age, sex, region, socioeconomic position, motivation to stop smoking, strength of urges to smoke) produces a population distribution of health or behavioural outcomes (bottom up). This is in contrast to cohort-level models which simulate a population by examining the average rate of disease/behaviour[10] within subgroups, which itself is based on the average values of other risk factors or characteristics (top down).

Microsimulation can also be used to provide insights into the potential effect of public health policies on a simulated population. Different policy scenarios can be applied to a simulated population that affect the probabilistic transitions between certain 'states' of interest that agents can be categorised into, such as smoking status. The projected outcomes in the 'treated' simulated population under an intervention scenario can then be compared with an 'untreated' simulated population who do not experience an intervention. If a real-world representative population sample is used to 'seed' the initial simulated population in the microsimulation, the outcomes can be segmented according to relevant sociodemographic characteristics, which also influence the probabilistic transitions that agents can undergo.

Recent macro-level modelling (using group and subgroup aggregates rather than individuals) in England has projected that overall declines in smoking will be accompanied by a reduction in absolute inequalities (the difference in smoking rates between socioeconomic groups), but not relative inequalities (the ratio of smoking rates between socioeconomic groups), which are likely to increase[10]. A microsimulation model can be leveraged to estimate how a given population health policy/scenario could change these trajectories and impact future disparities in smoking prevalence. Following policy implementation in the United States, one policy previously under review for potential implementation in the UK was to raise the legal age of tobacco sale from 18 to 21. Although the debate on this approach has evolved into one on the more comprehensive "smokefree generation" policy, theory behind Tobacco 21 is similar in that it seeks to restrict access to cigarettes and therefore initiation of smoking among young people[11]. This follows evidence that the increase in age of sale from 16 to 18 was effective in England both overall[12] and in terms of reducing socioeconomic inequalities in smoking initiation[2]. Evidence from the United States suggests that Tobacco 21 policies to have been effective in reducing smoking prevalence among young adults compared with control communities[13,14]. Modelling the increase in age of sale from 18 to 21, including its potential socioeconomic impact, can provide insights into the proposed 'smokefree generation' policy currently undergoing legislating procedure in UK parliament[7]. Another scenario that can be explored using microsimulation is the potential impact of changes in the distribution of use of popular smoking cessation aids such as e-cigarettes[5,15,16] and nicotine replacement therapy (NRT) in England. There is growing evidence on the benefit of e-cigarettes for smoking cessation in clinical settings[17] but also from use in the general population[5]. Under the UK government sponsored 'swap to stop' scheme, one in five people who smoke are to be offered e-cigarettes alongside behavioural support to boost smoking cessation in England[8]. Microsimulation can provide information on the impact on future smoking prevalence of this proposal by projecting the outcomes of switching the individuals attempting to quit with no support (currently representing the majority of quit attempts), or who use a widely available aid such as over-the-counter (OTC) NRT, to e-cigarettes.

Microsimulation has been used by researchers in the United States and the United Kingdom to simulate changes in smoking behaviour as a function of various policies[18,19], but to our knowledge these techniques have not yet been applied specifically to a Tobacco 21 or e-cigarette shift scenario in the UK smoking system context and explored equity focussed outcomes. This study aims to present insights from a microsimulation model when projecting the impact of two hypothetical scenarios - i) raising the legal age of tobacco sale to 21 and ii) shifting smokers attempting to quit using OTC NRT, or no support, to e-cigarettes - on socioeconomic and regional smoking rates and disparities in England.

Methods

This article complies with the Strengthening and Reporting of Empirical Simulation Studies (STRESS) guidelines[20].

The QuitSimX model

QuitSimX is a microsimulation model that projects individual-level smoking uptake and cessation in England. The model is seeded with real-world sociodemographic and smoking behaviour data from respondents in the Smoking Toolkit Study (STS). The STS is a representative survey of smoking behaviour in England, involving monthly cross-sectional household computer-assisted interviews. Each month a sample of approximately 2,450 adults aged 16+ years and over in Great Britain (1,700 in England, 450 in Scotland, 300 in Wales) is included. Data for the STS in England were first collected in November 2006. The survey uses a form of random location sampling whereby Great Britain is first split into 227,403 'Output Areas', each comprising of approximately 300 households. These areas are then stratified according to established geo-demographic characteristics and geographic region then randomly selected into an interviewer's list. Before analysis, data is weighted to be representative of the population using a rim (marginal) weighting technique[21]. This involves an iterative sequence of weighting adjustments whereby separate nationally representative target profiles are set (gender, working status, prevalence of children in the household, age, social grade and region) and the process repeated until all variables match the specified targets. More information on the STS is provided elsewhere[22].

From the STS, data were extracted from all surveyed individuals in England from the year 2013 and characteristics were assigned to simulated 'agents' in the microsimulation model. For all agents, values are extracted on age, gender, occupational social grade, region, survey weight and smoking status (mutually exclusive categories never smoker, smoker, quitter, ex-smoker). A *never smoker* is someone who has not smoked for more than one year in their lifetime, a *smoker* is someone who currently smokes, either daily or less than daily, a *quitter* is someone who is currently trying to quit, and whose latest quit attempt is shorter than one year, and an *ex-smoker* is someone who had quit smoking for more than one year.

Depending on which smoking state an agent is in, they can have additional characteristics which are initialised or turned off when an agent changes smoking status (Figure 1). Smokers are assigned a number of cigarettes smoked and motivation to stop smoking (MTSS)[23]. Quitters are assigned a quit length and a route to quit (i.e., a specific smoking cessation aid, including an option of using no aid). Ex-smokers are assigned a quit length.

General population dynamics are also applied to the model. All agents age as the model moves forward and are assigned a probability of dying during the next monthly progression of the model. Death depends on several variables including age, smoking status, gender and region and is parameterised using mortality rates from the Office for National Statistics (ONS) standardised regional mortality rates[24], Annual Population

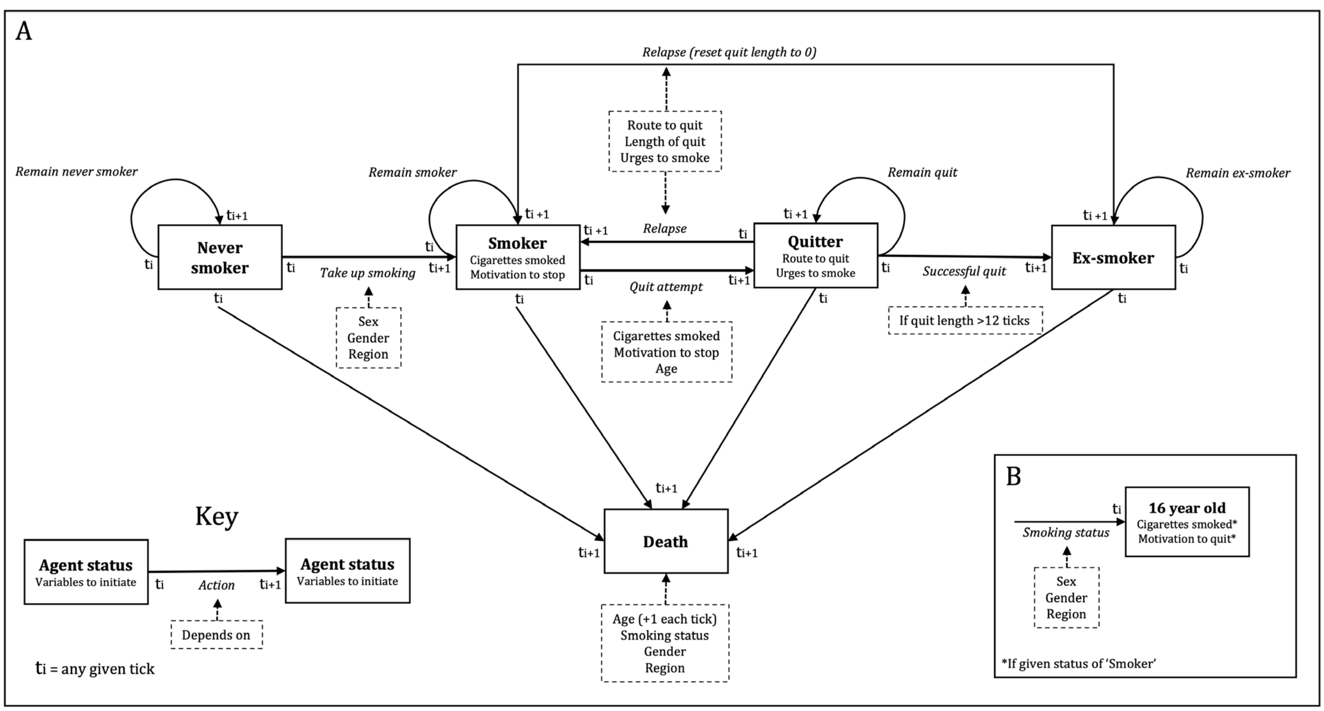

Figure 1. Summary of the QuitSimX microsimulation model.

Survey (APS) data[25] on smoking prevalence and a study estimating the relative risk of dying between smokers, ex-smokers and never smokers[26]. Birth is not included in the model as it is set up to make predictions only up to 10 years into the future and the population of interest is aged 16+ based on the STS. Agents younger than 16 are allocated a random birth month so that as the model moves forward in time agents turning 16 do not enter model in the same month. The number of agents with a given age are based on ONS data on regional population estimates for England and Wales 1971–2016[27]

A 'tick' is the fundamental time unit in the model, with each tick representing one month. At each tick, a number of probabilistically determined agent actions can take place within the simulation:

1. Agent death
2. Agent (*Never smoker*) takes up smoking
3. Agent (*Smoker*) undertakes a quit attempt
4. Agent (*Quitter/Ex-smoker*) relapse to smoking
5. Agent (*Quitter/Ex-smoker)* remain quit
6. Agent (*Quitter*) who have been on a quit attempt for a year change smoking status to *ex-smoker*
7. All agents age by tick length
8. Agents entering the model (16 year olds) are assigned a smoking status
9. Agent (*Smoker*) consume' a total amount of sticks (cigarettes) smoked since the last tick

The probability of an agent transitioning between smoking statuses at the upcoming tick is dependent upon their age, gender, and social grade. Depending on the transition in question – for example between a smoker and quitter, or an ex-smoker and smoker - the probability can also be dependent on smoking characteristics such as their motivation to stop smoking and the number of cigarettes smoked. The probability of a 16-year-old being assigned a smoking status as they enter the model is informed by a linear regression of the STS variable for smoking status over time among 16-year-olds.

A summary of the model logic for agent transitions is shown in Figure 1 below. More detail on model parameterisation and formulae, code for derivation of simulated prevalence data, and prevalence data is provided online in an open access data repository at https://osf.io/4n5d8/ (see data availability statement).

In panel A, the solid arrows represent time moving one tick (month) forward from any given tick (ti) to the next (ti+1). Each solid box represents the smoking status of an individual agent at ti or ti+1. The text above/below each arrow indicates actions that are occurring that lead to the change of status for an agent (for instance "Take up smoking" is between the statuses of " Never Smoker" and "Smoker"). Each dashed box represents the factors which each action is dependent upon (for instance, "Quit attempt" is dependent upon the agent's age, the number of cigarettes they have smoked and their assigned motivation to stop smoking. Panel B outlines how at each tick, 16 year-old agents enter the model and are assigned a smoking status based on their assigned sex, region and social grade. These agents are then subject to the dynamics in panel A.

Running the model

Setting parameters

To run a model, several parameters are specified. Parameters include the intervention start year, the number of years the simulation will run for, and probabilities of 1-year quit success for the following routes to quit smoking:

- Behavioural support
- NRT OTC
- Quitting without support (unaided quitting)
- Prescription medication (NRT, Varenicline, Bupropion)
- E-cigarettes

Once the parameters are selected, one or a combination of the two interventions below can be applied to the system.

Tobacco 21

An intervention in which the legal age of tobacco sale is increased to 21 years can be implemented by setting the start year of the intervention (e.g. 2019), entering an estimate for the reduction of smoking prevalence in agents age 16 years (e.g. 0.5 indicates the numbers of smoking 16-year-olds will be halved), and an estimate for the reduction in smoking uptake in agents aged 16–21 years (e.g. 0.5 indicates the number of 16–21-year-olds who take up smoking is halved).

Move quitters to e-cigarettes

An intervention which moves quitters to use e-cigarettes from other routes to quit can be implemented by setting the intervention start year, the number of years until the intervention reaches full-effect (i.e. reaches the desired proportion of quitters to move towards e-cigarettes), entering a value for the proportion of quitters moved towards e-cigarettes, and choosing which route to quit to move quitters from (behavioural support, prescription medication, NRT over-the-counter and unaided quitting). The movement of quitters occurs linearly over the number of years specified in the scenario set up. As an example, assuming 50% of quit attempts are made without support, an intervention moving 30% of these unaided quitters to e-cigarettes over three years would see a 5% increase by e-cigarette quits in year one ($0.5 \times 0.1 = 0.05$ or 5%), 10% increase by year two, and a 15% increase by year three, relative to the baseline scenario. The percentage of people quitting unaided would decrease correspondingly from year one to three.

Output and weighting
After setting the parameters and intervention details, the simulation is run for 10 years from the selected start date. It returns a data file with an estimate for prevalence of each smoking status (ex-smoker, non-smoker, quitter, smoker), within every possible 'minimal segment' - a combination of socio-demographic characteristics of the population for each month of the year. For instance, it provides the prevalence of smoking in January 2014 among females who are from social grade AB, are aged 16–24, and live in the London region, and so on.

Every agent in the simulated population has a weight based on the STS and at every tick, belongs to a 'minimal segment'. Each segment has a weight that is computed as the sum of weights of all the agents in the minimal segment they belong to.

For each tick within a given minimal segment, each smoking status is a fraction such that the combination of smoking statuses sums to one (100%). To examine the prevalence of a given smoking status in a broader demographic segment (e.g., combining males and females from social grade AB, aged 16–24, living in the London region), the status fraction within each minimal segment must be multiplied by the weight of that segment and added to the same derivative of the other segment, before dividing this value by the combined weight of each segment.

To illustrate:

- Group A (males) has 100 members and 50 are smokers. The smoking fraction is therefore 0.5. The weight of this group is 100.
- Group B (females) has 200 members and 50 are smokers. The smoking fraction is therefore 0.25. The weight of this group is 200.

The overall smoking fraction in A+B is therefore [100 × 0.5 + 200 × 0.25]/100+200 = 0.33 or 33%.

Analyses
The above computations are run on the model output data in R to arrive at a data frame estimating smoking prevalence according to selected socio-demographic subgroups, allowing a comparison between groups as to the absolute and relative change in prevalence under an intervention scenario vs a counterfactual 'no intervention' scenario where no intervention was applied to the system.

Equity impact of interventions
To examine the potential differential impact of each intervention scenario, the final smoking prevalence for each scenario across selected sociodemographic subgroups is described in terms of both absolute and relative change.

Absolute inequalities are examined by comparing the subgroups at the final timepoint in terms of their absolute difference in smoking prevalence. A smaller difference between the "disadvantaged" and "advantaged" groups under the intervention scenario compared with that under the no intervention scenario would represent a reduction in absolute inequalities.

Relative change in inequalities is examined by comparing the ratio of smoking prevalence among less advantaged and more advantaged groups at the start and the end of the simulation, for both the intervention and baseline (no intervention) scenario, respectively. A smaller ratio at the final timepoint compared with the start would indicate a reduction in relative inequalities. Moreover, if the intervention scenario had a smaller ratio than the no intervention scenario at the final timepoint this would indicate that it led to a greater reduction in inequalities.

The selected sociodemographic subgroups include social grade and region. Social grade is based on occupation[28]. Group ABC1 represents those with professional and managerial occupations and skilled manual workers, and C2DE representing those in routine and manual work, unemployed or on state benefits. Smoking prevalence among people in social grade C2DE is estimated to be twice that of those in social grade ABC1 in England[6]. Regional comparisons include the government office regions of North (collapsed North East and North West England), and London. This breakdown reflects established regional and economic smoking disparities in England, with higher rates in the North East and North West compared with London[29].

The analysis was run in R version 4.3.1, with underlying data and code available at https://osf.io/xtw6j/.

Results
Tobacco 21 scenarios – Model specification
The impact of raising the age of sale to 21 in selected social grades (ABC1 vs C2DE) and government office regions (London vs North and North West) in England

The Tobacco 21 scenario model is run over a 11-year timeframe, initiated in 2013 (the year of representative data used to seed the model), with the intervention starting in 2019 and ending in 2023. The scenario is run twice using different parameter values for the reduction in smoking prevalence. Scenario 'A' involves a reduction in smoking prevalence in 16-year olds of 40%, and in smoking uptake in 16–21 year olds of 30%. Scenario 'B' involves respective reductions of 80% and 60% in these groups. These values and others for 1-year quit success under different routes to quit are outlined in Table 1.

Tobacco 21 scenarios – model results
Smoking prevalence declines between 2013 to 2023 in all models and subgroups, but the absolute decline was greater among both Tobacco 21 scenarios compared with the baseline scenario (Figure 2a). Compared with 2013, the absolute difference in smoking between social grades is lower in 2023 under all scenarios. In 2023, the absolute difference in

Table 1. Tobacco 21 model parameters.

Parameter	Value
1-year quit success when using behavioural support	0.1
1-year quit success when using NRT OTC	0.04
1-year quit success when using prescription medication	0.075
1-year quit success when using e-cigarettes	0.075
1-year quit success when quitting unaided	0.032
Model start year	2013
Intervention start year	2019
Reduction in smoking prevalence in 16 year-olds	0.4, 0.8*
Reduction in smoking uptake in 16–24 year-olds	0.3, 0.6*

* Models run separately with updated estimates for reduction (scenario A and B). Values for quit success based on data from Cochrane Systematic Reviews[30–34]

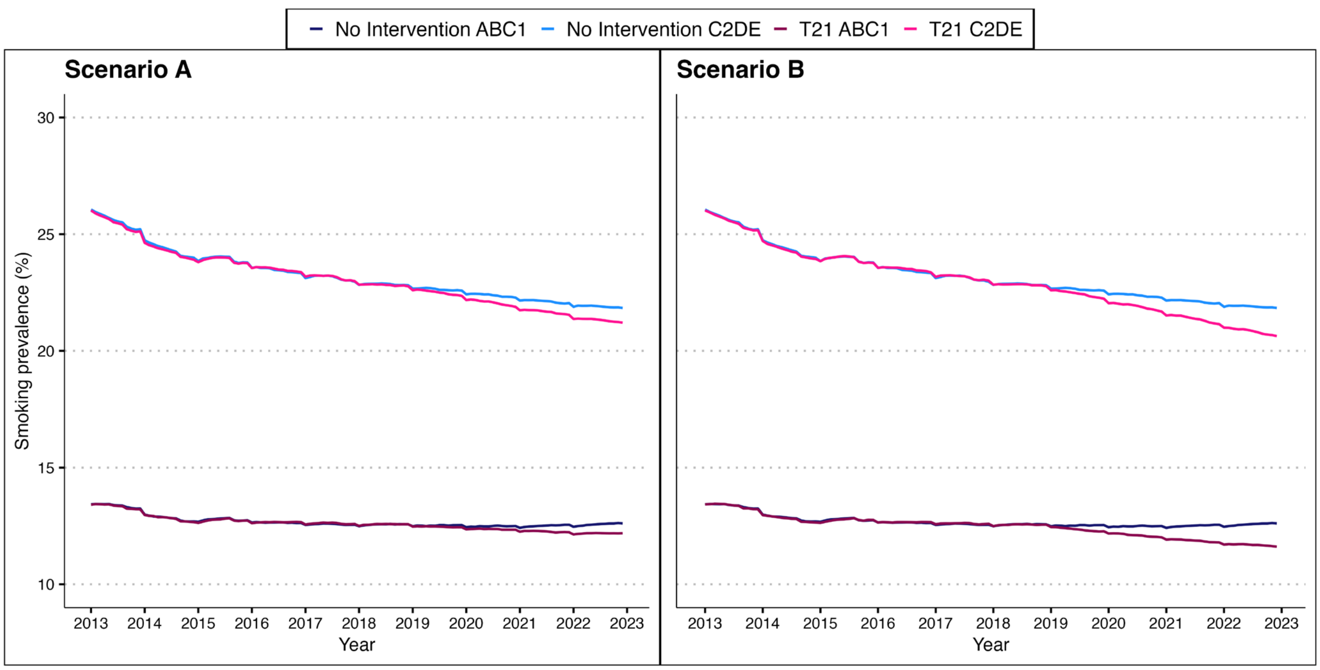

Figure 2. Smoking prevalence by social grade under Tobacco 21 scenarios A and B*. *Tobacco 21 scenario A: Reduction of smoking prevalence in 16-year olds = 40%; reduction in smoking uptake in 16-21 year olds = 30%; intervention start year = 2019. Tobacco 21 scenario B: Reduction of smoking prevalence in 16-year olds = 80%; reduction in smoking uptake in 16-21 year olds = 60%; intervention start year = 2019.

smoking prevalence between ABC1 and C2DE are similar under the no intervention and both Tobacco 21 scenarios (Table 2).

Regarding relative inequalities the ratio of smoking prevalence in C2DE to ABC1 is lower in 2023 for each scenario (baseline, A and B) compared with 2013. When comparing the ratios under each scenario in 2023 with each other, the relative inequality is slightly higher under scenario B (1.78) compared with scenario A (1.74) and the baseline scenario (1.73). A similar pattern of results was evidence according to region (North vs London; and Supplementary Appendix Table S2 and Figure S1).

Table 2. Absolute and relative inequalities in smoking prevalence under Tobacco 21 scenarios A and B by social grade compared with no intervention scenario.

	Start 2013	No intervention 2023	Scenario A 2023	Scenario B 2023
	Smoking prevalence (%)			
Overall	19.1	16.8	16.3	15.7
Social grade				
ABC1	13.4	12.6	12.2	11.6
C2DE	26.1	21.8	21.2	20.6
Difference	12.7	9.2	9.0	9.0
Ratio	1.95	1.73	1.74	1.78

* Tobacco 21 scenario A: Reduction of smoking prevalence in 16-year olds = 40%; reduction in smoking uptake in 16–21 year olds = 30%; intervention start year = 2019. Tobacco 21 scenario B: Reduction of smoking prevalence in 16-year olds = 80%; reduction in smoking uptake in 16–21 year olds = 60%; intervention start year = 2019.

E-cigarette scenarios – model setup

The impact of shifting routes to quit towards e-cigarettes from either NRT OTC or unaided quitting in selected social grades (ABC1 vs C2DE) and government office regions (London vs North and North West) in England

The e-cigarette scenario model is also run over a 11-year timeframe, initiated in 2015 (when e-cigarettes popularity increased[35]), with the intervention starting in 2016 and ending in 2025. This scenario is run several times using different parameter values for the proportion of quitters moved towards a quit method.

Scenario A involves moving 33% of quitters trying to quit using no support (unaided quitting) over to e-cigarettes, B moving 66% and C moving all (100%). These values and others for 1-year quit success under different routes to quit, and the time taken for the intervention to reach full effect are outlined in Table 3.

E-cigarette from OTC NRT scenarios – model results

Smoking prevalence declines between 2015 and 2025 among those in social grade C2DE, but not ABC1, under the baseline scenario and each scenario A-C (Figure 3 and Table 4). Compared with 2015, the absolute difference in smoking between social grades is smaller in 2025 under all scenarios. In 2025, the absolute difference in smoking prevalence between ABC1 and C2DE are similar under the baseline and all e-cigarette scenarios (Table 4).

Regarding relative inequalities, the ratio of smoking prevalence in C2DE and ABC1 is lower in 2025 for each scenario (baseline and A-C) compared with 2015. When comparing the ratios under each scenario in 2025 with each other, the relative inequalities are similar across groups (1.74). A similar pattern of results was apparent according to region (North vs London; Table 4 and Supplementary Appendix Figure S2)

E-cigarette from unaided quitting scenarios – model results

Smoking prevalence declines between 2015 and 2025 in C2DE, and to a lesser extent in ABC1, under the no intervention scenario and each scenario A-C. The decline is greater under all e-cigarette scenarios compared with the baseline scenario (Table 4 and Figure 4). Compared with 2015, the absolute difference in smoking rates between social grades is smaller in 2025 under all e-cigarette scenarios. In 2025 the difference graduated from A-C and is smallest under C (all unaided quit attempters switch to e-cigarettes) for both ABC1 and C2DE (Table 4).

Regarding relative inequalities, the ratio of smoking prevalence in C2DE and ABC1 is lower in 2025 for each scenario compared with 2015. When comparing the ratios under each scenario in 2025 with each other, the relative inequalities are similar across groups (1.74).

A similar pattern of results is apparent according to region, with the exception that there is a clear absolute decline in smoking from 2015–2025 under the baseline scenario in London. which is not so apparent for social grade ABC1 (Table 4 and Supplementary Appendix Figure S3).

Discussion

Microsimulation approaches permit researchers and policymakers to explore how unequal exposures and risk factors lead to differential risk among individuals within populations, and analyse emergent effects of policies across heterogenous populations of people[9]. Seeded using representative data of the population in England and 'real-world' estimates

Table 3. E-cigarette model parameters.

Parameter	Value
1-year quit success when using behavioural support	0.1
1-year quit success when using NRT OTC	0.04
1-year quit success when using prescription medication	0.075
1-year quit success when using e-cigarettes[a]	0.075
1-year quit success when quitting unaided	0.032
Model start year	2015
Intervention start year	2016
Years to reach full effect	3
Proportion of quitters moved towards e-cigarettes[b]	0.33, 0.66, All
Route to quit from which quitters moved to e-cigarettes[c]	NRT, UQ

[a] Models run with estimate for 1-year quit success of e-cigarettes to be similar to (0.075) prescription medication.

[b] Models run separately with different parameter values for proportion moved to e-cigarettes.

[c] Models run with route to quit as OTC NRT or UQ (unaided quitting).

of smoking and quitting-related indicators, the QuitSimX microsimulation highlighted the potential impact of iterations of two different policies on socioeconomic differences in smoking prevalence. Overall, regardless of socioeconomic position and assuming the highest impact on uptake that we state, if Tobacco 21 is introduced we could expect a ~3% reduction in overall smoking prevalence within 10 years. Similarly, there would be potential overall reductions of ~2% or 3% over 10 years if people are switched from OTC NRT or unaided quitting, respectively.

In the first set of simulations, the policy of raising the age of sale to 21 in 2019 was run under separate scenarios, each with different chosen values for the reduction in smoking prevalence in 16-year-olds (40% and 80%, respectively) and for the reduction in smoking uptake in 16–21 year olds (30% and 60%, respectively). In terms of inequalities, the absolute and relative inequalities according to social grade and region are smaller under all scenarios in 2023 compared with 2013. However, the apparently higher relative inequality ratio under the high impact tobacco 21 scenario (80% reduction in 16-year-old smoking prevalence and 60% reduction in 16–21 uptake) compared with the moderate impact scenario (40% reduction in 16-year-old smoking prevalence and 30% reduction in 16–21 uptake) and the counterfactual ‘no intervention’ scenario in 2023 highlight how relative inequalities may increase in response to tobacco 21 despite an overall decline in smoking prevalence in priority groups. If tobacco 21 or similar policies are introduced in England and the impact on smoking uptake is as large as postulated in our simulations, additional messaging and support should be targeted at priority groups to avoid increases in relative inequalities.

In the second set of simulations - scenarios where either 1/3, 2/3 or all OTC NRT users are switched to use an e-cigarette to quit smoking – there were modest declines in smoking overall compared with the counterfactual ‘no intervention’ scenario, but the impact is graduated, increasing in size with the proportion of NRT users switched to e-cigarettes. There are no meaningful differences in the absolute or relative inequalities in 2025, regardless of scenario.

In the final set of simulations - scenarios where either 1/3, 2/3 or all those attempting to quit without support (unaided quitting) are switched to use an e-cigarette to quit smoking – once again the size of absolute and relative inequalities declined from 2015 to 2025 by social grade and region, but relative to each other the values for absolute and relative inequalities in 2025 under the counterfactual ‘no intervention’ and e-cigarette switch scenarios are similar. This suggests that increasing the use of e-cigarettes in quit attempts would achieve considerable declines in smoking without exacerbating existing inequalities.

Together these simulations illustrate the potential equity impact of population-level policies to reduce smoking rates. Interventions to boost smoking cessation and reduce uptake can be effective overall, but ultimately have an unbalanced impact and affect health inequality if the rate of decline in smoking in one group is greater than in the other[36]. However, in such circumstances the size of the increase in absolute and relative inequality must be weighed in the context of the overall reductions in smoking. For instance, as demonstrated in our simulations involving the implementation of the tobacco 21 law (Table 2), at the end of the simulation period (the year 2023) the rate of smoking is approximately one percentage point lower in all socioeconomic groups under the high impact tobacco 21 scenario compared with the counterfactual ‘no intervention’ scenario. At the same time, the absolute differences in 2023 smoking prevalence between

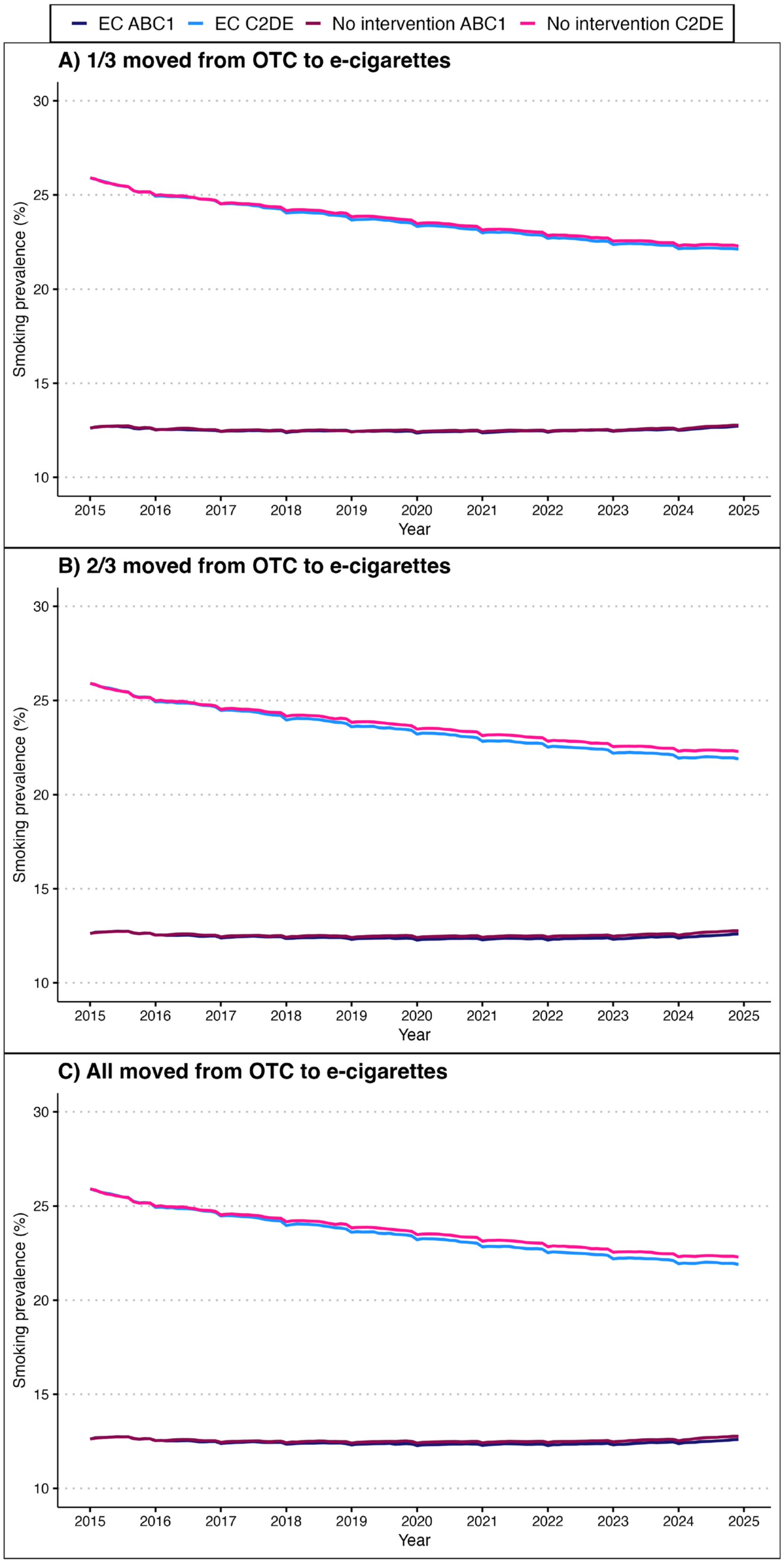

Figure 3. Smoking prevalence by social grade under e-cigarette from OTC NRT scenarios.

Table 4. Absolute and relative inequalities in smoking prevalence under respective NRT OTC, and unaided quitting, to e-cigarette scenarios A, B and C by social grade and region, compared with baseline scenario.

	Start 2015	No intervention 2025	NRT OTC Scenario A 2025	NRT OTC Scenario B 2025	NRT OTC Scenario C 2025	UQ Scenario A 2025	UQ Scenario B 2025	UQ Scenario C 2025
	Smoking prevalence (%)							
Overall	18.7	17.1	17.0	16.9	16.7	16.7	16.3	15.8
Social grade								
ABC1	12.6	12.8	12.7	12.6	12.5	12.5	12.1	11.8
C2DE	25.9	22.3	22.1	21.9	21.8	21.7	21.2	20.6
Difference	13.3	9.5	9.4	9.3	9.3	9.2	9.1	8.8
Ratio	2.06	1.74	1.74	1.74	1.74	1.74	1.75	1.74
Region								
London	16.1	15.2	15.1	15.0	14.8	14.9	14.3	14.0
North	22.9	19.8	19.8	19.5	19.4	19.2	18.8	18.2
Difference	6.8	4.6	4.7	4.5	4.6	4.3	4.5	4.2
Ratio	1.42	1.30	1.31	1.30	1.31	1.29	1.31	1.30

NRT OTC = Nicotine Replacement Therapy Over the Counter; UQ = Unaided quitting

[1] NRT OTC scenario A/UQ scenario A: 1/3 of all NRT OTC users /UQ quit attempters switch to e-cigarettes.

[2] NRT OTC scenario B/UQ scenario B: 2/3 of all NRT OTC users/UQ quit attempters switch to e-cigarettes.

[3] NRT OTC scenario C/UQ scenario C: all NRT OTC users/UQ quit attempters switch to e-cigarettes.

socio-economic groups in the 'no intervention' and the tobacco 21 scenarios are minimal, and the relative inequality is marginally higher under the higher impact policy scenario (1.78) compared with the baseline scenario (1.73). If this trend is to continue in a monotonic fashion (something which cannot be assumed), despite there being no change in absolute inequalities, the relative inequality would necessarily increase due to size of the relative decline being larger in the denominator than the numerator (e.g. moving from 20/10 to 15/5 is an increase in relative inequality from 2 to 3). In summary, the overall impact of a policy on relative inequalities in smoking behaviour should be examined in the context of the absolute decline in smoking between groups of interest.

Under the baseline scenario of the e-cigarette intervention models, the smoking prevalence of social grade ABC1 appeared to reach a 'steady-state' and did not decline over the simulated period. This has been observed in real world data from the smoking toolkit study (see www.smokinginengland.info/monthly-tracking-kpi) where since late 2018 smoking rates have somewhat plateaued in the same social grade[22]. While the COVID-19 pandemic may have disrupted declines in smoking prevalence due to increases in uptake among young people and late relapse among ex-smokers (after >1 year of abstinence)[37], this flattening of the decline may also reflect the absence of major tobacco control initiatives or a 'floor effect' beyond which further declines in smoking rates are difficult to achieve at the population level[38,39].

The aim of this study was to demonstrate the process and utility of a microsimulation model in exploring the impact of different policy scenarios on smoking rates. A key limitation of the current study is its application to the current policy and population smoking dynamics, which have changed since the model process was initiated. In addition, the choice of parameters is guided by evidence from studies in the real world but is nonetheless subjective. Small value, or evidence-based choices, in the numbers entered into the model can lead to divergent effects, especially in the uncertain longer term. This highlights the importance of transparency when reporting the methods and outcomes of simulation studies. In future the model will be expanded to address other more contemporary policy changes and to project further forward to guide decision-making and prioritisation in tobacco control.

The UK government aims to reduce the prevalence of smoking in England from the present 13–14% to ≤5% - termed 'smoke-free' - by the year 2030[40]. It is hoped that through its policy proposals for a 'smokefree generation' and interventions such as the e-cigarette scheme 'swap-to-stop' e-cigarette will help achieve these sustained reductions in smoking prevalence. Additional considerations and targeted approaches may needed to accelerate the decline in smoking across priority groups such as those with greater socioeconomic disadvantage where smoking prevalence and associated health burden[41] remains highest (in 2018 smoking prevalence was 25% among those with routine and manual occupations compared with 10% among those with managerial/ professional occupations[6]).

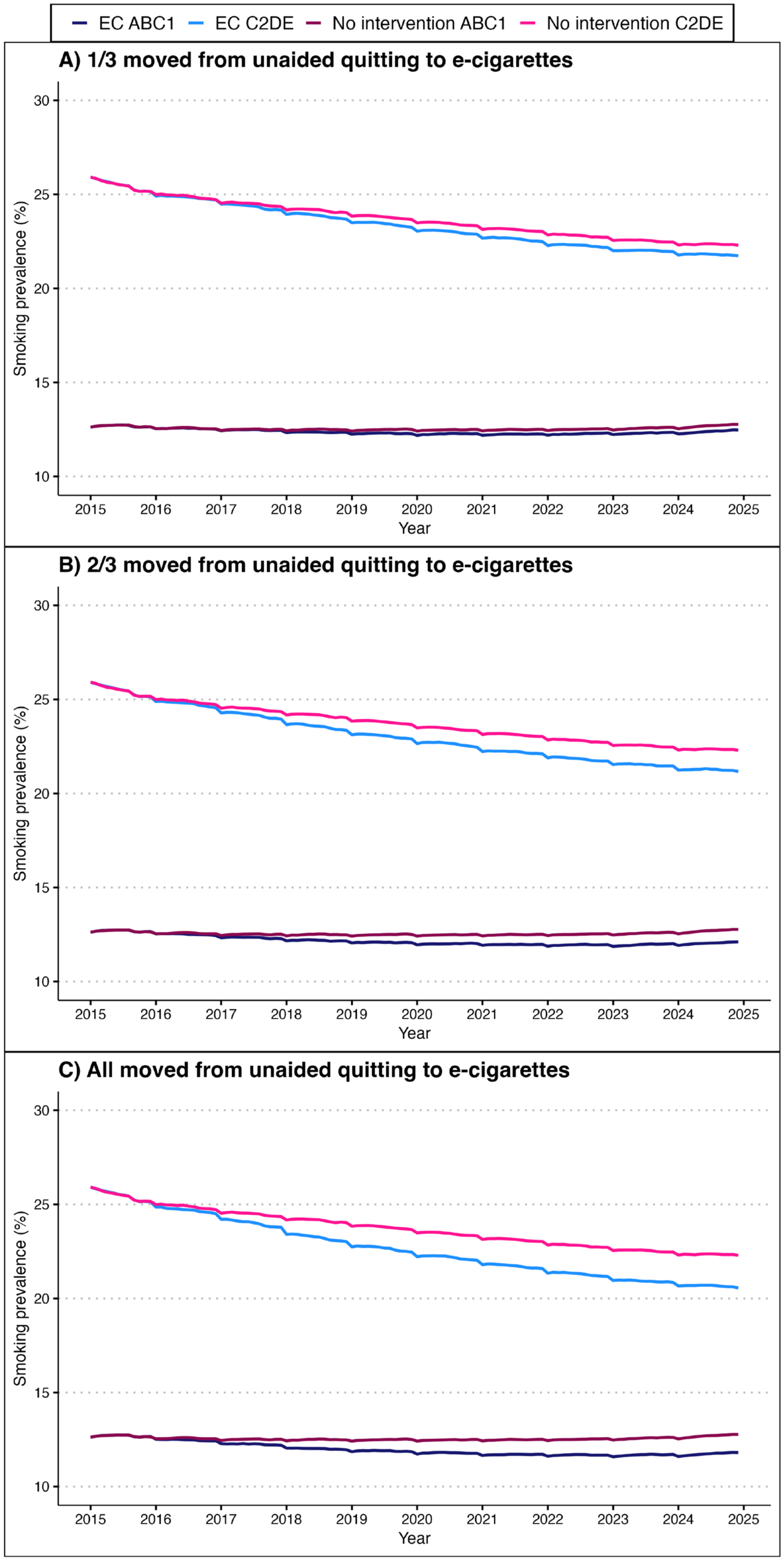

Figure 4. Smoking prevalence by social grade under e-cigarette from unaided quitting scenarios by social grade.

In conclusion, a microsimulation model of smoking and quitting in England under tobacco 21 and e-cigarette policies highlights that relative absolute and relative inequalities may remain similar between intensive policy scenarios and counterfactual 'no intervention' scenarios despite the policies having a considerable impact on reducing overall smoking rates.

Ethics and consent statement

Ethical approval for the Smoking Toolkit Study was granted by the University College London Ethics Committee (0498/001; 2808/005) most recently in 17/4/2020. The data in the Smoking Toolkit Study are not collected by UCL and are anonymised when received by UCL. All respondents are given a written information sheet about the study and provide informed verbal consent.

Data availability statement

Open Science Framework: QuitSimX: Microsimulation model of smoking prevalence in England.

https://doi.org/10.17605/OSF.IO/XTW6J[42]

This project contains the following underlying data, available under a CC0 universal license:

1. Underlying R code for smoking prevalence derivation.
2. Smoking prevalence data under each simulated scenario.
3. Model parameterisation and formulae
4. STRESS guideline checklist.

Data are available under the terms of the Creative Commons Zero "No rights reserved" data waiver (CC0 1.0 Public domain dedication).

Software availability statement

Source code available from: https://github.com/lorenkock/QuitSimX-microsimulation

Archived software available from: https://doi.org/10.17605/OSF.IO/XTW6J[42]

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