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Electronic Cigarettes, Nicotine Use Trends, and Use Initiation Ages among US Adolescents from 1999–2018

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Abstract

Background and Aims: Recent nicotine use trends raise concerns that electronic cigarettes (ECs) may act as a gateway to cigarettes among adolescents. The aims of this study are to examine prevalence trends of exclusive EC use, exclusive cigarette use, and dual use, and to determine the corresponding ages of initiation, and investigate hypothetical trends in total nicotine use and cigarette use in the absence of ECs among US adolescents.

Design: Data from the National Youth Tobacco Survey (NYTS) were used to statistically model trends in the prevalences of each user group, and their initiation ages. Projections from counterfactual models based on data from 1999–2009 (before EC introduction) were compared to actual trends based on data from 1999–2018. Rigorous error analyses were applied, including Theil proportions.

Setting: USA.

Participants: Adolescents aged 12–17 years who are established exclusive cigarette users (≥100 cigarettes smoked AND ≤100 days vaped), established exclusive EC users (<100 cigarettes smoked AND >100 days vaped), and established dual users (≥100 cigarettes smoked AND >100 days vaped), based on cumulative lifetime exposure (N≈12,500–31,000 per wave).

Results: Exclusive cigarette use prevalence declined from 1999–2018, while exclusive EC use and dual use prevalences increased since their introduction in 2009. The age of cigarette initiation began a slight increase after 2014, whereas the age for EC use remained approximately constant and was higher than that of cigarettes. The counterfactual comparison results were consistent with ECs not increasing the number of US adolescent nicotine users, and in fact diverting adolescents from cigarettes.

Conclusions: ECs may have offset conventional smoking among US adolescents between 2010–2018 by maintaining the total nicotine use prevalence and diverting from more harmful

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COMPETING INTERESTS
None declared.

conventional smoking. Additionally, EC users initiate at older ages relative to conventional smokers, which is associated with lower risk.

INTRODUCTION

ECs have steeply risen in popularity in the United States (1), raising public health concerns about the current landscape of nicotine use in adolescents (2–4). However, the rise in ECs has been offset by a corresponding decline in conventional cigarette smoking (1, 5), leaving it unclear whether the total number of nicotine users has changed. The negative health effects of ECs are estimated to be 5% that of conventional cigarettes (6, 7), suggesting potential for harm reduction. However, concerns have been raised about the disproportionate targeting of ECs to young users, such as with marketing (8) and flavorings (9, 10). Moreover, it has been suggested that ECs may have a causal effect on subsequent conventional cigarette smoking among adolescents (11). Meta analyses (11, 12) have associated EC use with future cigarette use in adolescents, but methodological research has shown bias in these effect estimates (13–15), motivating novel analyses.

In the worst-case scenario, ECs are used at an earlier age, are increasing the total number of nicotine users (16–18), and are causing the surplus population of users to then use conventional cigarettes which are more harmful (19). On the other hand, in the best-case scenario, the trends in ECs may reflect a population-level transition to a less-harmful product, and may even divert adolescents from using conventional cigarettes (20, 21). This remains controversial because of limited data available on EC use, as well as heavy confounding between ECs and conventional cigarette use. For example, youth who use ECs are highly similar to those who use conventional cigarettes with respect to a variety of risk factors (22, 23). In fact, shared risk factors largely account for the apparent effect of ECs on conventional smoking among adolescents (13). Therefore, it remains challenging to isolate the causal effect of ECs on nicotine use patterns among US adolescents.

Key to understanding the effects of ECs is estimating the counterfactual, i.e. what the conventional smoking prevalence would have looked like in the absence of ECs. One way to do this is to examine population-level changes in prevalence of nicotine product use, which a few notable studies have done. Levy et al. (24) showed that year-by-year decreases in conventional smoking accelerated by 2–4 times after ECs became popular. West et al. (25) showed that increases in EC use among adolescents were overwhelmingly attributable to those who were already established cigarette users and who had initiated first with cigarettes. Walker et al. (26) showed that ECs may be displacing conventional smoking based on trend analysis of repeated cross-sectional data of New Zealand adolescents. However, very little research has been done examining and projecting prevalence trends continuously across time, focusing on how these trends changed before and after the introduction of ECs (2010–2018).

This paper is a population-level approach at circumventing these challenges by statistically modeling trends in exclusive cigarette use, exclusive EC use, and dual use of cigarettes and ECs, using 1) actual data over two decades from the National Youth Tobacco Survey (NYTS), and 2) projected data under the counterfactual scenario in which ECs are absent.

The aims of this study are to examine a) prevalences of each user group over time, b) ages of initiation and established use of each group, and c) whether the actual use trends differ from the counterfactual projections. Trends are modeled using best fits and validated with statistical methods such as Theil proportions (27), which represents a rigorous and novel approach to examining the competing accounts of the current EC landscape in the US.

METHODS

Sample

Data on smoking behaviour were taken from the NYTS (28), a complex multi-stage probability sample which surveys ~15,000 to ~36,000 youths aged 9–21 years on their tobacco use and associated risk factors. Results from 1999–2018 were used which represent repeated independent cross-sectional samples at each wave. The data were reduced by filtering for ages 12–17 years leaving ~12,500 to ~31,000 observations per wave.

The decision to collect data on adolescents aged 12 –17 years is justified by the relatively low level of tobacco product use initiation before the age of 12, and the legality of tobacco product purchase changing at 18.

Measures

Exclusive cigarette users were defined from surveys across 1999–2014 as adolescents who had smoked ≥100 cigarettes (5 packs) in their lifetime. With the availability of more data on cumulative EC use, exclusive cigarette users were defined from surveys across 2015–2018 with the additional requirement of having used ECs for ≤100 days.

Exclusive EC users were defined from surveys across 2015–2018 as adolescents who had used ECs for >100 days in their lifetime, and who had smoked <100 cigarettes in their lifetime. This cutoff differs from that of exclusive cigarette use (i.e. inclusion vs exclusion of exactly 100) due to the NYTS questionnaire response options.

Dual users were defined from surveys across 2015–2018 as adolescents who had smoked ≥100 cigarettes in their lifetime, and who had used ECs for >100 days. Our definition of dual use describes cumulative lifetime exposure to both products, and the cross-sectional nature of NYTS data precludes examining temporal ordering of product use.

The decision to define use by cumulative lifetime exposure, as opposed to initiation, was based on two primary factors; 1) initiation is less important than cumulative lifetime use for long-term health outcomes (29); and 2), systematic errors in ever use of ECs have been identified in the NYTS prior to 2014 due to a change in questionnaire design (30).

Weighted prevalences of exclusive cigarette users, exclusive EC users, and dual users to total adolescents were calculated at each wave. Up to and including the year 2009, the prevalence of EC and dual users were taken to be approximately zero prior to ECs becoming available.

Average ages of use initiation for exclusive cigarette users, exclusive EC users, and dual users were calculated at each wave.

Analyses

Details of our statistical analyses are available in the Supplementary Information online. All data processing, analysis, and plotting were performed in Python with the following packages: NumPy, Uncertainties, Matplotlib, and SciPy. Code will be supplied upon a reasonable request to the authors. The following summarizes the statistical methods employed.

Survey-weighted prevalences for each user group (exclusive cigarette use, exclusive EC use, and dual use) were estimated at each wave, with standard error estimates.

Analysis of total nicotine use—We defined the prevalence of total nicotine use as the sum of exclusive cigarette use prevalence + exclusive EC use prevalence + dual use prevalence at each wave.

An *actual best fit* curve was found for total nicotine use across 1999–2018. A *counterfactual best fit* curve was found across 1999–2010 and extrapolated from 2010–2018, representing a scenario in which ECs never came onto the market. These curves were derived with weighted regressions. The shape of each curve, as explained in the Supplementary Information, was decided by minimizing the root mean square error (RMSE). The RMSE was complemented by use of Theil proportions (27) which break down the mean squared error (MSE) into three components; the bias inequality proportion U^B, the unequal variation inequality proportion U^V, and the unequal covariation inequality proportion U^C, whose relative proportions describe the differences between the data and fit. The MSE components indicate the source of the error, and the RMSE indicates how greatly this error affects the best fit.

The potential change of total nicotine users was investigated by comparing the actual and counterfactual curves in the following way: for each year after 2010, the total nicotine use prevalence was estimated from the actual and counterfactual best fit functions. The absolute difference between the actual and counterfactual prevalences on a given year were divided by the error on the difference, giving a dimensionless constant M. M then represents the difference between the actual and counterfactual prevalences, relative to their combined errors. Assuming a Gaussian distribution of errors, a value of $M<1$ indicates that the difference is likely just due to uncertainty; therefore the curves describe approximately the same trend (i.e. the introduction of ECs is not likely to have caused a change in the total prevalence of nicotine users, which corresponds to the null hypothesis). On the other hand, a value of $M>1$ indicates that the difference is not likely due to uncertainty, and the curves describe different trends (i.e., the introduction of ECs is likely to have either increased the total prevalence of nicotine users (if the actual curve is above the counterfactual), or decreased the total prevalence of nicotine users (if the actual is below the counterfactual)).

Analysis of total cigarette use—We defined the prevalence of total cigarette use as the sum of exclusive cigarette use prevalence + dual use prevalence at each wave.

An *actual best fit* curve was found for total cigarette use across 1999–2018. A *counterfactual best fit* curve was found across 1999–2010 and extrapolated from 2010–2018, representing a scenario in which ECs never came onto the market. These curves were derived with weighted regressions. Again, the shape of each curve was decided by minimizing the RMSE, and Theil proportions were applied.

The potential gateway from EC use to cigarette use was investigated by comparing the actual and counterfactual curves, in the same way as described in the analysis on total nicotine use. Here, a value of $M<1$ indicates that the difference is likely just due to uncertainty, therefore the curves describe approximately the same trend (i.e. the introduction of ECs is not likely to have caused a change in the total prevalence of cigarette use, corresponding to the null hypothesis). On the other hand, a value of $M>1$, indicates that the difference is not likely due to error, and the curves describe different trends (i.e., the introduction of ECs is likely to have either increased the total prevalence of cigarette use (if the actual is above the counterfactual, corresponding to the gateway hypothesis), or decreased the total prevalence of cigarette use (if the actual is below the counterfactual, corresponding to the diversion hypothesis)).

Analysis of initiation age—Survey-weighted average initiation ages for exclusive cigarette use and exclusive EC use were estimated at each wave, with standard error estimates.

For dual use, the average initiation age at each wave was found by finding the initiation ages of cigarette use and EC use for a given user, taking the highest of the two (since they only become a dual user once meeting the use requirements of both products), then averaging these ages across all dual users.

RESULTS

The trends of nicotine use prevalence are shown in Figure 1.

Looking at Figure 1(A), established cigarette use has declined monotonically from ~12% of adolescents in 1999, to an all-time minimum of ~1% of adolescents in 2018. A breakdown of the MSE reveals $U^C \approx 0.992$, indicating that the covariance of the best-fit model data and measurement data differ, so the best fit and measurements have the same mean and trend but differ point-by-point. However, the RMSE of the fit is 0.464, which indicates that the fit is very good relative to the range of y-axis data (a numerical change of ~11), and that the point-by-point difference is minimal.

Looking at Figure 1(B), established EC use has increased since its introduction in 2009 to an all-time maximum of ~2.5% of adolescents in 2018, which is still below the 2014 level of cigarette use prevalence. The MSE breakdown reveals $U^V \approx 0.278$, and $U^C \approx 0.625$, indicating that the best-fit model data does not simulate the noise of the measurement data, so the best fit and measurements have the same mean and trend but differ point-by-point due to this noise. The RMSE≈0.447, which indicates that the fit is good relative to the y-axis range of ~3, and that the point-by-point difference is small.

Looking at Figure 1(C), established dual use has also increased since its introduction in 2009 to an all-time maximum of ~1% of adolescents in 2018, the same as 2018's minimum level of cigarette use prevalence. The MSE breakdown reveals $U^C \approx 0.974$, similar to 1(A). However, the RMSE≈0.158, which indicates that the fit is reasonable relative to the y-axis range of ~1, and that the point-by-point difference is small.

The trends of use initiation age are shown in Figure 2.

Looking at Figure 2(A), the cigarette initiation age has remained relatively stable at ~11.7 years (besides some noise) from 1999–2012, after which a clear, albeit low magnitude, upward trend is observed. The MSE breakdown reveals $U^V \approx 0.308$, and $U^C \approx 0.689$, similar to 1(B). The RMSE≈0.168, which indicates that the fit is acceptable relative to the y-axis range of ~0.7, and that the point-by-point difference is somewhat small.

Looking at Figure 2(B), the EC initiation age has shown some fluctuation around an approximate mean of ~13.5 years. This is significantly greater than the initiation age of cigarettes. The MSE breakdown reveals $U^V \approx 0.830$, indicating that the best-fit model is always the mean of the measurement data (with approximately zero variance), but the measurement data is cycling over time, so the correlation is weakened. Since the model fit is not meant to simulate this cycling, this suggests an unsystematic error. The RMSE≈0.215, which indicates that the fit is acceptable relative to the y-axis range of ~0.5, and that the point-by-point difference is somewhat small.

Looking at Figure 2(C), the dual use initiation age has also shown some fluctuation around a decreasing gradient from ~13.4 years to ~12.8 years on average across 2015–2018. The MSE breakdown reveals $U^V \approx 0.263$, and $U^C \approx 0.710$ indicating that the best-fit model data does not simulate the cycling of the measurement data, so the best fit and data have the same mean and trend but differ point-by-point because the measurements contain cycles. The RMSE≈0.254, which indicates that the fit is acceptable relative to the y-axis range of ~0.9, and that the point-by-point difference is somewhat small.

Figure 3 compares the projected counterfactual trend in total nicotine use prevalence over time using data from before the introduction of ECs, to the actual trend in total nicotine use prevalence over time.

The area enclosed by the 95% confidence bounds on the *actual* best fit lies completely within the area enclosed by the bounds on the *expected* counterfactual best fit. The M values range from ~0.65 in 2010 to ~0.77 in 2018. All of these satisfy $M<1$, indicating that the difference is likely due to error, so the curves describe approximately the same trend.

Figure 4 compares the projected counterfactual trend in cigarette use prevalence over time using data from before the introduction of ECs, to the actual trend in the total prevalence of cigarette use (exclusive cigarette use + dual use) over time.

The area enclosed by the 95% confidence bounds on the *actual* best fit diverges downward from the area enclosed by the bounds on the *expected* counterfactual best fit. The M values range from ~1.6 in 2010 to ~2.5 in 2018. All of these satisfy $M>1$, indicating that the difference is not likely due to error, and the curves describe different trends.

DISCUSSION

This study aimed to examine the trends in use prevalence and initiation age for adolescents aged 12–17 with respect to cigarettes and/or ECs, as well as the possible impacts of EC use on cigarette use and total nicotine use. Our results showed that exclusive cigarette use among adolescents has declined monotonically since 1999, and in 2018 hit an all-time minimum of ~1% of adolescents. All EC use has increased since their introduction circa 2009, however their maxima still fall short of recent cigarette use prevalence. Additionally, the EC initiation age varies minimally over time, and is higher than that of cigarettes. Furthermore, the introduction of ECs is likely to have had little to no impact on the total number of adolescents using nicotine, and is likely diverting adolescents from cigarettes.

Previous literature has found younger age of initiation to be a risk factor for later nicotine use (31, 32). Thus, the risk for adolescents using ECs may be lower than that of adolescents using cigarettes. Moreover, the marketing of ECs to younger adolescents (8–10) does not appear to reduce the age of exposure to nicotine. However, the dual use initiation age shows some decline, albeit to an age still greater than that of cigarettes. This warrants further study with forthcoming data.

The total nicotine use prevalence findings present a novel examination of the actual trend vs the expected trend in the counterfactual scenario of no ECs. The lack of statistical difference besides error between these trends indicates that the total number of users does not significantly differ in reality vs the counterfactual case. Thus, the introduction of ECs is not likely to have caused a change in the total prevalence of nicotine users. This contradicts previous studies, which have suggested that ECs bring in a new population of adolescent nicotine users (16–18).

Despite findings from meta analyses (11, 12) associating EC use with future cigarette use in adolescents, our findings show that the actual total cigarette use is consistently and increasingly lower than the expected trend under the counterfactual scenario of no ECs. The significant statistical differences imply the introduction of ECs is likely to have decreased the total prevalence of cigarette users by diverting adolescents to exclusive EC use.

The prevalences reported in our study are markedly lower than those reported in many other surveillance reports (1, 5, 33). This was a deliberate choice to present prevalence using definitions of established cumulative lifetime use, rather than more common definitions based on lifetime use (having ever tried a cigarette or EC) or current use (any cigarette or EC use within the past 30 days). Our decision was motivated by the fact that it is established use, rather than initiation or experimental use, that is relevant to population-level health risks (29). This difference in definition should be taken into consideration when comparing our findings with previous research.

Implications for Harm Reduction

Our findings have several implications for the harm reduction potential of ECs. First, given that ECs are estimated to be only 5% as harmful as conventional cigarettes (6, 7), any amount of offsetting conventional cigarettes by ECs should lead to harm reduction from a population health perspective (34). In the current case, this offsetting appears to occur both with respect to a stable prevalence of the use of *any* tobacco product, and a decrease in the use of conventional cigarette smoking. Second, since the age of initiation is considered a risk factor for chronic smoking (31, 32), the fact that age of smoking initiation is occurring *later* after the appearance of ECs, as well as the higher initiation age for ECs relative to cigarettes, may represent further harm reduction with respect to subsequent nicotine use.

Limitations

Several limitations should be noted; first, data here are cross-sectional, which limits the ability to draw causal conclusions and prevents consideration of temporal ordering of product use. Similarly, the use of counterfactual models may not necessarily establish causality due to possible confounding influences. For example, policy changes have occurred over the considered time frame in the US, including the Family Smoking Prevention and Tobacco Control (FSPTC) Act in 2010. However, policies aimed at reducing nicotine use can sometimes have counterproductive effects (35, 36). Given that the FDA's implementation of this Act has come under criticism and that there is little research examining its effectiveness, the FSPTC Act's actual effect on nicotine use prevalence remains ambiguous. Due to the novelty of the current study with respect to comparing actual and counterfactual trends at the population level, we considered policy analysis outside the scope of our study. Having found evidence of a potential diversion effect using counterfactual trend modeling, future research should examine other population-level confounders such as policies.

Also, data on EC use were limited, especially with respect to cumulative lifetime exposure which was only available from 2015 onward. Similarly, the self-reported nature of survey data may limit the accuracy of these findings, and the binning of survey response options may cause some skew.

Furthermore, the implications of our results apply only to 2010–2018, and do not necessarily apply to projections beyond 2018. Changes in the EC market landscape, such as the rapid popularity of JUUL (in particular nicotine salts) circa 2018 among adolescents (37, 38), may alter future trends. Additionally, policy changes such as forthcoming regulations of ECs by the Food and Drug Administration (FDA) in the US will likely alter prevalence trends. Future research may consider piecewise trend modeling for distinct eras punctuated by rapid changes in product availability and regulatory environment.

Strengths

The strengths of this paper include the novelty of the counterfactual projections utilized, which offer a valuable contrast to biased analyses (13–15) which dominate this field. Data were taken from sources with large sample sizes and nationally representative weights, producing results generalisable to the US adolescent population. This combined with the methodological rigour taken provides strong statistically grounded findings, which were validated with insightful error analysis methods.

Conclusions

In summary, a population-level examination of adolescent nicotine use behaviours has shown that the presence of ECs has not resulted in an earlier initiation age of nicotine products, nor is it likely to have increased the total prevalence of adolescent nicotine users or acted as a gateway to cigarette use. In fact, the results are more consistent with ECs diverting adolescents from cigarette use. Since ECs are estimated to be only 5% as harmful as cigarettes (6, 7), ECs have substantial implications for harm reduction among youth.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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REFERENCES

1. Johnston LD, Miech RA, O’Malley PM, Bachman JG, Schulenberg JE, Patrick ME. Monitoring the Future national survey results on drug use 1975–2018: Overview, key findings on adolescent drug use. Ann Arbor; 2019.
2. Corey CG, Wang B, Johnson SE, Apelberg B, Husten C, King BA, et al. Notes from the field: Electronic cigarette use among middle and high school students -- United States, 2011–2012. CDC; 2013.
3. Wang TW, Gentzke A, Sharapova S, Cullen KA, Ambrose BK, Jamal A. Tobacco Product Use among Middle and High School Students -- United States, 2011–2017. 2018.
4. Choi K, Fabian L, Mottey N, Corbett A, Forster J. Young adults’ favorable perceptions of snus, dissolvable tobacco products, and electronic cigarettes: findings from a focus group study. Am J Public Health. 2012;102(11):2088–93. [PubMed: 22813086]
5. Gentzke AS, Creamer M, Cullen KA, Ambrose BK, Willis G, Jamal A, et al. Signs: Tobacco Product Use Among Middle and High School Students — United States, 2011–2018. 2019.
6. McNeill A, Brose L, Calder R, Bauld L, Robson D. Evidence review of e-cigarettes and heated tobacco products 2018 A report commissioned by Public Health England. London: Public Health England; 2018 2018.
7. McNeill A, Hajek P. Underpinning evidence for the estimate that e-cigarette use is around 95% safer than smoking: authors’ note. Public Health England; 2018.
8. Kirkpatrick MG, Cruz TB, Unger JB, Herrera J, Schiff S, Allem JP. Cartoon-based e-cigarette marketing: Associations with susceptibility to use and perceived expectations of use. Drug Alcohol Depend. 2019;201:109–14. [PubMed: 31207451]
9. Dai H, Hao J. Flavored Electronic Cigarette Use and Smoking Among Youth. Pediatr. 2016;138(6).
10. Morean ME, Butler ER, Bold KW, Kong G, Camenga DR, Cavallo DA, et al. Preferring more e-cigarette flavors is associated with e-cigarette use frequency among adolescents but not adults. PloS one. 2018;13(1):e0189015. [PubMed: 29300749]
11. National Acadmies of Sciences E, and Medicine,,. Public Health Consequences of E-Cigarettes. Washington, DC; 2018.
12. Soneji S, Barrington-Trimis JL, Wills TA, Leventhal AM, Unger JB, Gibson LA, et al. Association Between Initial Use of e-Cigarettes and Subsequent Cigarette Smoking Among Adolescents and Young Adults: A Systematic Review and Meta-analysis. JAMA Pediatrics. 2017;171(8):788. [PubMed: 28654986]

13. Kim S, Selya A. The relationship between electronic cigarette use and conventional cigarette smoking is largely attributable to shared risk factors. Nicotine Tob Res. In press.;In press.
14. Rosenbaum PR. Observational Studies. 2nd Edition ed. New York NY: Springer Verlag; 2002.
15. Rosenbaum PR. Design of Observational Studies: Springer Science+Business Media, LLC; 2010.
16. Barrington-Trimis JL, Urman R, Berhane K, Unger JB, Cruz TB, Pentz MA, et al. E-Cigarettes and Future Cigarette Use. Pediatr. 2016;138(1).
17. Goniewicz ML, Knysak J, Gawron M, Kosmider L, Sobczak A, Kurek J, et al. Levels of selected carcinogens and toxicants in vapour from electronic cigarettes. Tob Control. 2014;23(2):133–9. [PubMed: 23467656]
18. Dutra LM, Glantz SA. High international electronic cigarette use among never smoker adolescents. J Adolesc Health. 2014;55(5):595–7. [PubMed: 25344030]
19. Chaffee BW, Watkins SL, Glantz SA. Electronic Cigarette Use and Progression From Experimentation to Established Smoking. Pediatr. 2018;141(4).
20. Hajek P, Etter JF, Benowitz N, Eissenberg T, McRobbie H. Electronic cigarettes: review of use, content, safety, effects on smokers and potential for harm and benefit. Addiction. 2014;109(11):1801–10. [PubMed: 25078252]
21. Current McGraw D. and future trends in electronic cigarette use. Int J Psychiatry Med. 2015;48(4):325–32. [PubMed: 25817527]
22. Kwon E, Seo DC, Lin HC, Chen Z. Predictors of youth e-cigarette use susceptibility in a U.S. nationally representative sample. Addict Behav. 2018;82:79–85. [PubMed: 29501011]
23. Wills TA, Sargent JD, Knight R, Pagano I, Gibbons FX. E-cigarette use and willingness to smoke: a sample of adolescent non-smokers. Tob Control. 2016;25(e1):e52–9. [PubMed: 26261237]
24. Levy DT, Warner KE, Cummings KM, Hammond D, Kuo C, Fong GT, et al. Examining the relationship of vaping to smoking initiation among US youth and young adults: a reality check. Tob Control. 2019;28(6):629–35. [PubMed: 30459182]
25. Modeling longitudinal and multilevel data: Practical uses, applied approaches, and specific examples. Mahwah, NJ: Lawrence Erlbaum Associates; 2000.
26. Walker N, Parag V, Wong SF, Youdan B, Broughton B, Bullen C, et al. Use of e-cigarettes and smoked tobacco in youth aged 14–15 years in New Zealand: findings from repeated cross-sectional studies (2014–19). The Lancet Public Health. 2020.
27. Theil H Applied Economic Forecasting. Amsterdam: North Holland Publishing Company; 1966.
28. Prevention CfDCa. National Youth Tobacco Survey. Centers for Disease Control and Prevention; 1999–2018.
29. Villanti AC, Niaura RS, Abrams DB, Mermelstein R. Preventing Smoking Progression in Young Adults: the Concept of Prevescalation. Prev Sci. 2019;20(3):377–84. [PubMed: 29525899]
30. Delnevo CD, Gundersen DA, Manderski MTB, Giovenco DP, Giovino GA. Importance of Survey Design for Studying the Epidemiology of Emerging Tobacco Product Use Among Youth. Am J Epidemiol. 2017;186(4):405–10. [PubMed: 28369184]
31. Kandel DB, Yamaguchi K, Chen K. Stages of progression in drug involvement from adolescence to adulthood: further evidence for the gateway theory. J Stud Alcohol. 1992;53(5):447–57. [PubMed: 1405637]
32. Chassin L, Presson CC, Sherman SJ, Edwards DA. The natural history of cigarette smoking: predicting young-adult smoking outcomes from adolescent smoking patterns. Health Psychol. 1990;9(6):701–16. [PubMed: 2286181]
33. Wang TW, Gentzke AS, Creamer MR, Cullen KA, Holder-Hayes E, Sawdey MD, et al. Tobacco Product Use and Associated Factors among Middle and High School Students — United States, 2019; 2019.
34. Nutt DJ, Phillips LD, Balfour D, Curran HV, Dockrell M, Foulds J, et al. Estimating the Harms of Nicotine-Containing Products Using the MCDA Approach. European Addiction Research. 2014;20(5):218–25. [PubMed: 24714502]
35. Deutsch ME. Less-Toxic Cigarette Use May Backfire. Science. 2009;325:944.
36. Friedman AS. How does electronic cigarette access affect adolescent smoking? J Health Econ. 2015;44:300–8. [PubMed: 26583343]

37. Hammond D, Wackowski OA, Reid JL, O'Connor RJ, team ITCPEP. Use of JUUL E-cigarettes Among Youth in the United States. Nicotine Tob Res. 2018.

38. King BA, Gammon DG, Marynak KL, Rogers T. Electronic Cigarette Sales in the United States, 2013–2017. JAMA. 2018;320(13):1379–80. [PubMed: 30285167]

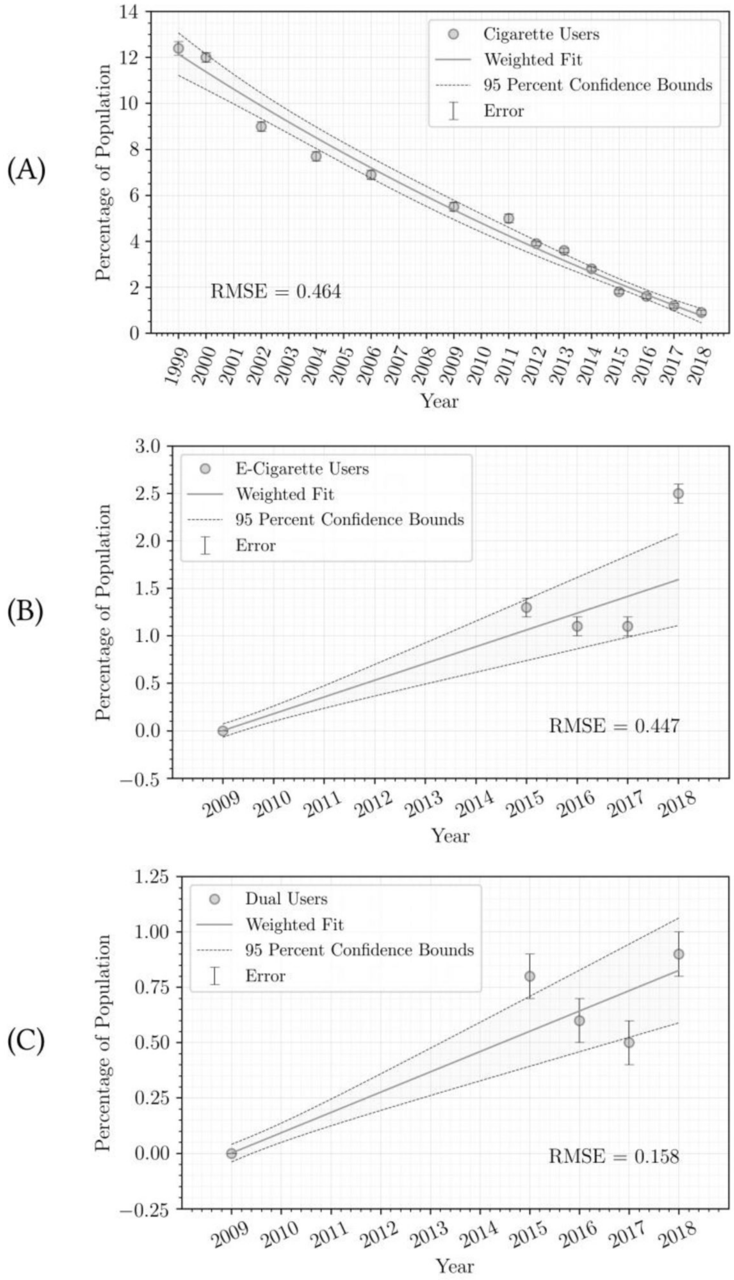

Figure 1: Nicotine Use Prevalence Trends.

The prevalence of adolescents aged 12–17 who are (A) established exclusive cigarette users (≥100 cigarettes smoked AND ≤100 days vaped), (B) established exclusive e-cigarette users (<100 cigarettes smoked AND >100 days vaped), and (C) established dual users (≥100 cigarettes smoked AND >100 days vaped), against time, based on NYTS data. The weighted best-fit curves are of the forms $y = ae^{bx} + c$ for (A), and $y = ax + b$ for (B) and (C), which yielded the lowest root mean squared errors (RMSE). The data are weighted by their errors.

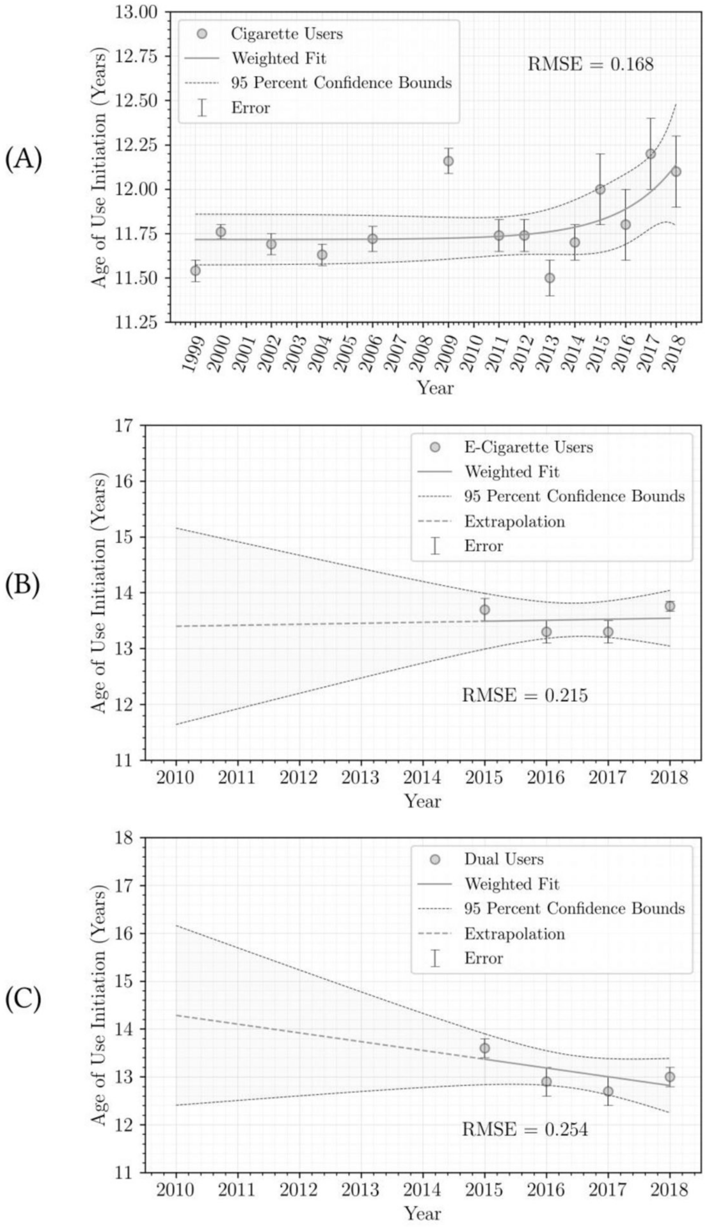

Figure 2: Age of Nicotine Use Initiation Trends.

The age of first use for adolescents aged 12–17 using (A) cigarettes, (B) e-cigarettes, and (C) both (dual use), against time, based on NYTS data. The weighted best-fit curves are of the forms $y = ae^{bx} + c$ for (A), and $y = ax + b$ for (B) and (C), which yielded the lowest root mean squared errors (RMSE). The data are weighted by their errors.

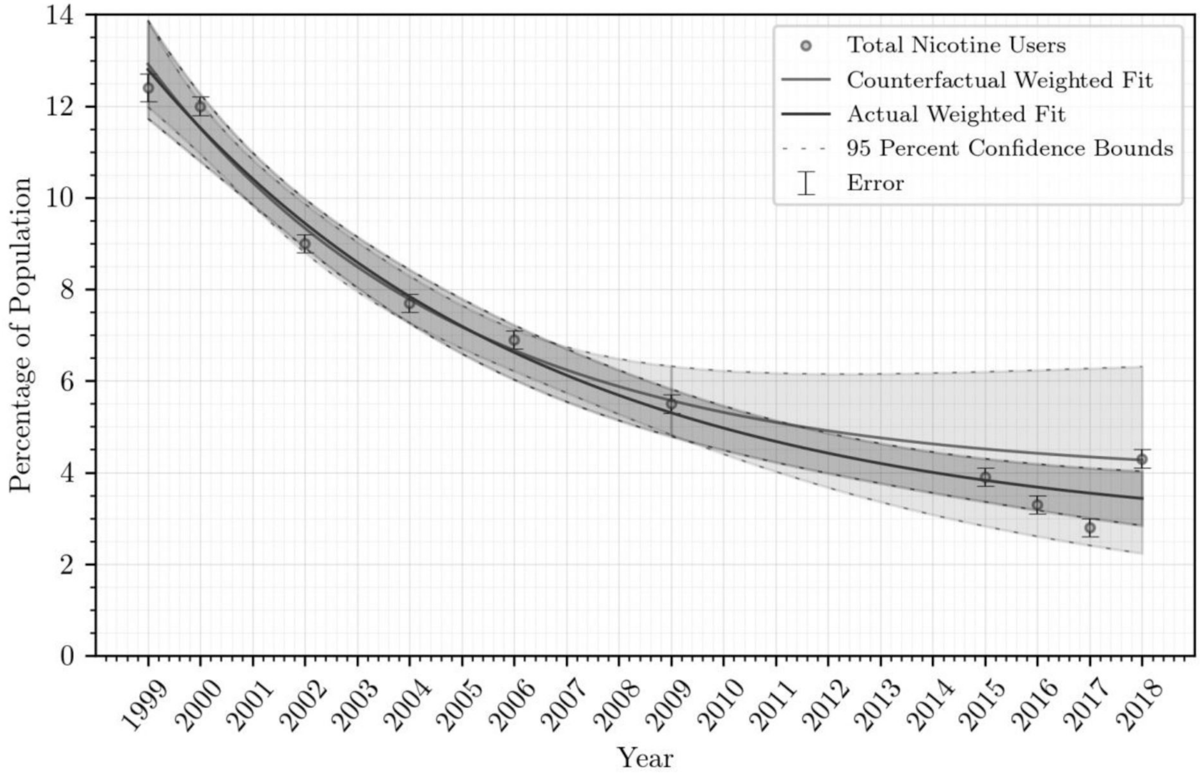

Figure 3: Total Nicotine Use Prevalence Trends.

The darker curve shows the total prevalence of adolescents aged 12–17 who are established nicotine users, including exclusive cigarette users (≥100 cigarettes smoked AND ≤100 days vaped), exclusive e-cigarette users (<100 cigarettes smoked AND >100 days vaped), and dual users (≥100 cigarettes smoked AND >100 days vaped), against time, based on NYTS data across 1999–2018. The lighter curve shows the percentage of just established exclusive cigarette users against time based on NYTS data across 1999–2009, before e-cigarettes were introduced. The latter curve is then extrapolated from 2009–2018. These weighted best-fit curves are of the form = $ae^{bx} + c$, which yielded the lowest root mean squared errors (RMSE). The data are weighted by their errors.

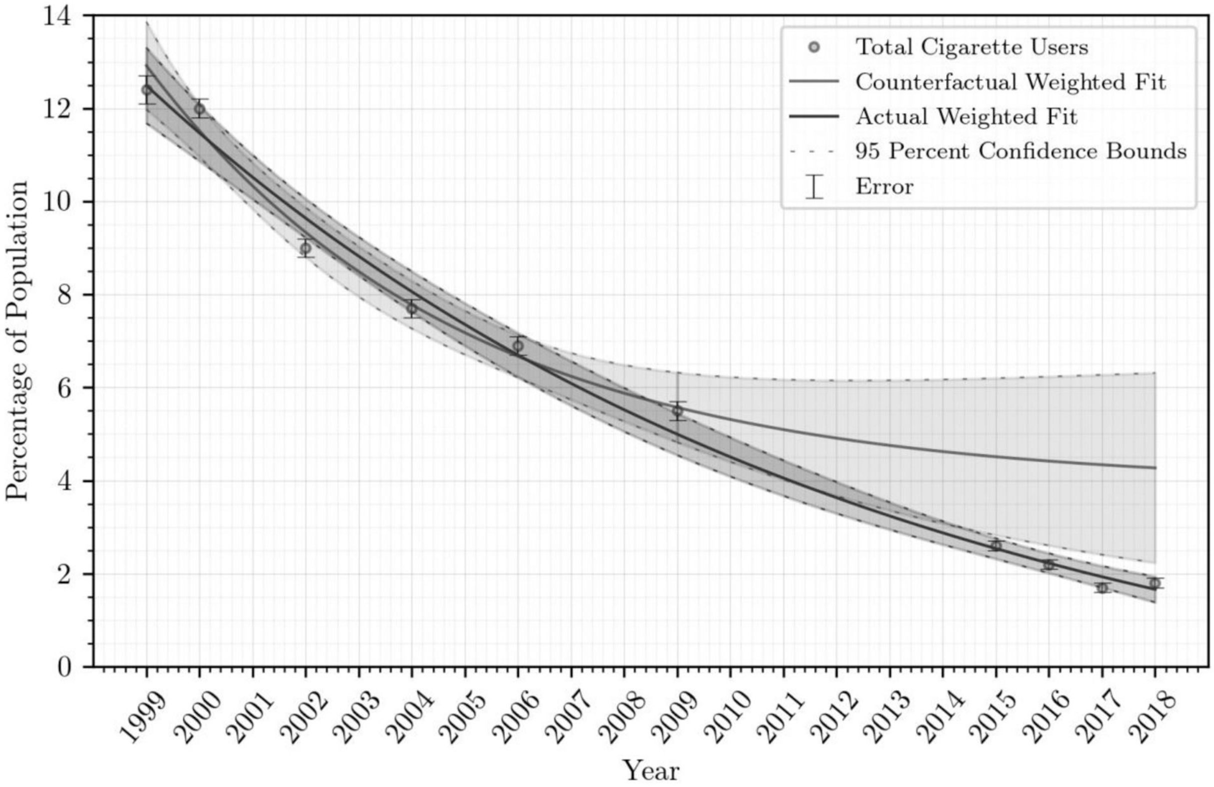

Figure 4: Total Cigarette Use Prevalence Trends.

The darker curve shows the total prevalence of adolescents aged 12–17 who are established cigarette users, including exclusive cigarette users (≥100 cigarettes smoked AND ≤100 days vaped) and dual users (≥100 cigarettes smoked AND >100 days vaped), against time, based on NYTS data across 1999–2018. The lighter curve shows the percentage of just established exclusive cigarette users against time based on NYTS data across 1999–2009, before e-cigarettes were introduced. The latter curve is then extrapolated from 2009–2018. These weighted best-fit curves are of the form = $ae^{bx} + c$, which yielded the lowest root mean squared errors (RMSE). The data are weighted by their errors.