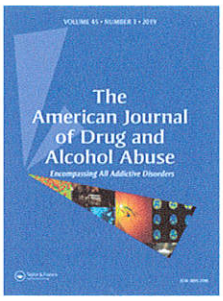

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ORIGINAL ARTICLE

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A quasi-experimental evaluation of marijuana policies and youth marijuana use

Rebekah Levine Coley, PhD[a], Summer Sherburne Hawkins, PhD, MS[b], Marco Ghiani, PhD[c], Claudia Kruzik, BA[a], and Christopher F. Baum, PhD[b,c,d]

[a]Lynch School of Education, Department of Counseling, Developmental, and Educational Psychology, Boston College, Chestnut Hill, MA, USA; [b]School of Social Work, Boston College,McGuinn Hall, Chestnut Hill, MA, USA; [c]Department of Economics, Boston College, Maloney Hall, Chestnut Hill, MA USA; [d]Department of Macroeconomics, German Institute for Economic Research (DIW Berlin), Berlin Germany

ABSTRACT

Background: Marijuana use carries risks for adolescents' well-being, making it essential to evaluate effects of recent marijuana policies.

Objectives: This study sought to delineate associations between state-level shifts in decriminalization and medical marijuana laws (MML) and adolescent marijuana use.

Methods: Using data on 861,082 adolescents (14 to 18+ years; 51% female) drawn from 1999 to 2015 state Youth Risk Behavior Surveys (YRBS), difference-in-differences models assessed how decriminalization and MML policy enactment were associated with adolescent marijuana use, controlling for tobacco and alcohol policy shifts, adolescent characteristics, and state and year trends.

Results: MML enactment was associated with small significant reductions (OR = 0.911, 95% CI [0.850, 0.975]) of 1.1 percentage points in current marijuana use, with larger significant declines for male, Black, and Hispanic (2.7–3.9 percentage points) adolescents. Effects of MML increased significantly with each year of exposure (OR = 0.980, 95% CI [0.968, 0.992]). In contrast, decriminalization was not associated with significant shifts in use for the sample as a whole, but predicted significant declines in marijuana use among 14-year olds and those of Hispanic and other ancestry (1.7–4.4 percentage points), and significant increases among white adolescents (1.6 percentage points). Neither policy was significantly associated with heavy marijuana use or the frequency of use, suggesting that heavy users may be impervious to such policy signals.

Conclusion: As the first study to concurrently assess unique effects of multiple marijuana policies, results assuage concerns over potential detrimental effects of more liberal marijuana policies on youth use.

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Introduction

Marijuana is the most popular illicit drug in the US among adolescents (1,2), with 15% of 9th graders and 28% of 12th graders reporting having used marijuana in the past month (3). Marijuana use also varies by race/ethnicity, with Black and Hispanic adolescents being more likely to use marijuana than white adolescents, and males more likely to use marijuana than females, although gender gaps appear to be closing in recent cohorts (3). Rates of adolescent marijuana use and attitudes regarding marijuana have shown small shifts in recent years, although patterns are inconsistent. For example, rates of youth marijuana use showed small declines in the first few years of the 21st century prior to increasing in the past decade. In contrast, adolescent attitudes concerning perceptions of risk have declined notably, with smaller declines in both disapproval of marijuana use and perceived availability (4). Yet marijuana clearly carries risks: use is associated in the short term with cognitive and behavioral deficits including impaired judgment, memory, and motor coordination (5). Negative effects of long-term and heavy use include addiction as well as lowered IQ, brain development, educational achievement and attainment, and life satisfaction, with risks notably elevated for those who initiate use in adolescence (5).

Given the risks of marijuana use, particularly for those who initiate use early and heavily, it is essential to delineate how government policies affect the rate and intensity of marijuana use among adolescents. Marijuana policies have shifted dramatically in recent years, driven primarily by state ballot and legislative initiatives. An early wave of state-wide decriminalization efforts – laws which typically remove criminal penalties (and sometimes civil penalties) for personal possession or use of marijuana – passed in the 1970s.

CONTACT Rebekah Levine Coley Ph.D coleyre@bc.edu Counseling, Developmental & Educational Psychology, Boston College, 140 Commonwealth Ave., Chestnut Hill, MA 02467

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As the high social costs of strict drug incarceration policies became more evident (6), marijuana decriminalization efforts have returned, with 21 states enacting decriminalization policies in the past decade. On a second policy front, efforts to legalize medical marijuana for treatment of chronic pain and symptoms associated with a host of medical conditions began in the 1990's, with policies now covering 29 states and the District of Columbia (7).

Although both decriminalization and medical marijuana policies restrict possession and use of marijuana to adults, they may indirectly affect adolescents. Access and signaling theories suggest that such policies may increase availability and access while decreasing perceptions of harm, hence leading to increased adolescent use of marijuana (8–10). Evidence of signaling effects of marijuana policy has been demonstrated among adult populations, while findings have been more mixed for adolescents (9–11). Further, changes in perceptions of access have been found primarily among adults as of yet (8,10).

Focusing on the most rigorous evidence, rather limited empirical attention has been directed at delineating the effects of marijuana decriminalization on adolescents, with inconsistent results and most work focusing on the likelihood of any use rather than frequency of use (12,13). Miech et al. found that 12th grade students in California were more likely to use marijuana and less like to perceive marijuana use as a health risk compared to students in other states after the enactment of marijuana decriminalization legislation in 2010 (12). In contrast, a review of the literature and analysis of Youth Risk Behavior Survey (YRBS) data by Ammerman et al. did not find sufficient evidence of differences in adolescent marijuana use before and after marijuana decriminalization legislation (13). Numerous studies have assessed links between medical marijuana laws (MMLs) and youth marijuana use, with most failing to identify a positive association using rigorous quasi-experimental methods and rather finding that use was higher in states prior to the enactment of MMLs (1,8,14–18). This suggests that other factors, such as more liberal attitudes, may be associated with both shifts in marijuana laws and the prevalence of adolescent use of marijuana (11,14,15,19), indicating the importance of adjusting for such underlying biasing factors.

As such, we argue for the importance of assessing the unique effects of multiple marijuana (and related substance use) policies. One of the primary limitations of prior research on decriminalization and medical marijuana policies and adolescent use of marijuana is the failure to assess the two policies concurrently in order to delineate their unique roles in promoting or inhibiting adolescent marijuana use. For example, in one of the more rigorous quasi-experimental analyses, Johnson and colleagues (1) used nationally representative data from the YRBS to assess the effects of medical marijuana policies on youth use of marijuana. Although they assessed both the enactment and the restrictiveness of such policies and considered dichotomous indicators of both any and heavy youth use (defined as ≥ 20 times per month) of marijuana, their analysis did not adjust for marijuana decriminalization or related policies. If states which pass medical marijuana laws are those with more generally liberal legal restrictions on marijuana, then unmeasured heterogeneity may bias results related to medical marijuana policy enactment. Similarly, research suggests that other policies targeting substances commonly used by youth, most importantly alcohol and cigarettes, may lead to substitution or spillover effects on marijuana use (20,21). As such, it is essential to evaluate the unique and joint effects of both decriminalization and medical marijuana policies on the early initiation and use of marijuana products among youth while also adjusting for other related policies that have been shown to affect youth substance use behaviors.

Secondly, prior research has paid limited attention to the potential for marijuana policies to differentially affect subpopulations of youth. There are numerous reasons to hypothesize that racial/ethnic and sex subgroups may respond differently. For example, although Black and white adolescents have been shown to use marijuana at relatively comparable rates, with Blacks' use about 30% higher, Blacks are 3 to 4 times more likely than whites to be arrested for marijuana possession (22,23). Due to differences in legal repercussions, racial subgroups may respond differently to the shifting marijuana policy landscape. Relatedly, research has found that despite increasingly similar rates of use, males are disproportionately likely to be arrested for marijuana possession compared to females (23). From these patterns, we might expect that populations previously at higher risks of legal repercussions (such as Blacks and males) may be more responsive to policy shifts which signal decreasing legal responses to marijuana use. Age is a third factor that may moderate how youth respond to marijuana policy shifts, with older adolescents perhaps being more likely than younger peers to experience increased access to marijuana following decriminalization and medical marijuana policies targeting adults. Given the risks associated with heavy marijuana use (5), it is also essential to further assess the effects of policy shifts on adolescents' frequency of use, which few prior studies have considered.

To address these limitations in prior research, this study sought to examine the unique effects of both

decriminalization and medical marijuana policies on adolescent marijuana use, adjusting for policies targeting the most common adolescent substances (alcohol and cigarettes), and to test differential policy effects by key subgroups of adolescents defined by age, race/ethnicity, and sex.

Methods

Data

Data were drawn from the Youth Risk Behavior Survey (YRBS), a biennial survey conducted since 1991 of the health risk behaviors of 9th through 12th grade students attending public and private schools in the United States. Students completed anonymous self-administered questionnaires during a regular class period. The YRBS uses a two-stage cluster sampling design with a minimum response rate of 60% for state data to be included and weighted to produce state-level representative samples (3,24). Additional information on YRBS methodology is available elsewhere (3,24). The Boston College Institutional Review Board reviewed this study and considered it exempt.

In order to focus on recent cohorts of youth and capitalize on the myriad shifts in marijuana policy in the 21st century, we analyzed 9 years of YRBS data (1999 through 2015) for 45 states (Table 1) (25). Our analytic sample included 861,082 of the 986,230 students in the YRBS. Adolescents were excluded if information was missing on marijuana use (35,241), cigarette use (47,744), strata (25,983), race (22,891), sex (6,346), or age (3,856) or the student was younger than age 14 years (7,559). Exclusion analyses indicated

Table 1. Adolescent marijuana use and marijuana policy enactment by state: Youth Risk Behavior Survey, 1999–2015 (N = 861,082).

State	Years	N	%[a]	% Marijuana use[b]	Medical Marijuana	Decriminalization
AK	03, 07–15	7,226	0.3	19.8	Mar. 4, 1999	1975[c]
AL	99–05, 09–15	10,607	1.6	17.7		
AR	99, 01, 05–15	12,219	1.0	18.3		
AZ	03–15	17,188	2.1	21.9	Apr. 14, 2011	
CA	15	1,789	12.7	22.3	Nov. 6, 1996	1976
CT	05–15	12,726	1.4	22.8	May 4, 2012	Jul. 1, 2011
DE	03–15	16,723	0.3	24.6	Jul. 1, 2011	Dec. 18, 2015
FL	03–15	34,508	6.1	20.0		
GA	03–13	10,673	3.3	18.2		
IA	05, 07, 11	4,171	1.3	13.4		
ID	03–15	11,321	0.6	15.4		
IL	07–15	13,707	4.5	20.1	Jan. 1, 2014	
IN	03–11, 15	10,945	2.4	18.9		
KS	05–13	8,610	1.1	14.2		
KY	03–15	14,535	1.4	16.7		
LA	07–13	3,962	1.2	14.7		
MA	99–15	27,896	2.2	26.5	Jan. 1, 2013	Jan. 2, 2009
MD	05–15	101,601	1.9	19.2	Jun. 1, 2014	Oct. 1, 2014
ME	01–15	37,231	0.5	21.5	Dec. 22, 1999	1976
MI	99–15	30,204	3.7	19.9	Dec. 4, 2008	
MO	99–09, 13, 15	12,255	2.2	20.1		
MS	99–03, 07–15	12,525	1.0	17.3		
MT	99–15	28,233	0.4	21.9	Nov. 2, 2004	
NC	01–15	26,426	3.2	21.3		
ND	99–15	15,339	0.3	16.6		
NE	03, 05, 11–15	11,724	0.6	13.9		
NH	03–15	22,358	0.5	25.3	Jul. 23, 2013	
NJ	01, 05, 09–13	8,151	3.1	20.7	Jul. 18, 2010	
NM	05–15	29,470	0.7	25.0	Jul. 1, 2007	
NV	99–09, 13,15	13,136	0.9	19.6	Oct. 1, 2001	Oct. 1, 2001
NY	03–15	71,274	6.2	19.1	Jul. 5, 2014	1977
OH	99,03–07,11,13	9,356	4.9	20.9		1975
OK	03–15	10,782	1.4	17.7		
PA	15	2,653	3.9	17.4		
RI	01–15	18,850	0.4	25.0	Jan. 3, 2006	
SC	99, 05–15	11,376	1.5	19.2		
SD	99–15	13,377	0.3	16.6		
TN	03–13	11,483	1.9	20.0		
TX	01, 05–13	23,129	9.7	19.7		
UT	99–13	12,073	1.2	8.6		
VA	11–15	11,510	2.8	16.6		
VT	99–11	49,084	0.2	26.9	Jul. 1, 2004	Jun 6, 2013
WI	99–13	17,150	2.2	19.5		
WV	99, 03–15	12,082	0.7	20.8		
WY	99–15	19,444	0.2	17.8		

[a]Weighted % of total sample size
[b]Weighted average over all available waves
[c]Marijuana was recriminalized in 1990 by ballot measure then again decriminalized by the courts in 2003 possession of less than four ounces) prior to legalization of recreational marijuana in 2015.

small differences between the analytic and full sample, with the latter being slightly younger, more likely to be white, and more likely to be female (Supplementary Table 1). Although statistically significant, these differences were consistently less than 1 percent. It is also essential to note that school-based samples such as the YRBS exclude youth who have dropped out of high school, and hence underrepresent the most disadvantaged populations.

Marijuana use

Adolescents were asked, "During the past 30 days, how many times did you use marijuana?", delineated as 0, 1 or 2, 3 to 9, 10 to 19, 20 to 39, or 40+ times. We created three variables describing current marijuana use. First, to assess variability in the frequency of marijuana use, we recoded this nonlinear scale by coding categories to their midpoint (0, 2, 6, 15, 30, and 40 times) to create a linear count variable of frequency of use. Second, we created a dichotomous variable indicating any use, defined as no (0 times) versus yes (1–40+ times). Similar to prior research (1), we also created a dichotomous variable to capture heavy use of marijuana, defined as no (0–19 times) versus yes (20+ times in the past 30 days).

Medical marijuana and decriminalization laws

Medical marijuana laws (MML) and decriminalization laws were coded using data derived from medicalmarijuana.procon.org and mpp.org (the Marijuana Policy Project). MML enactment excluded states that legalized only the use of the nonpsychoactive marijuana extract (cannabidiol) or required physicians to prescribe marijuana (an illegal action under federal law) as opposed to recommend marijuana (an action protected by free speech between doctor and patient). Decriminalization was defined as not imposing jail time for possession of marijuana. Medical marijuana laws (MML) and decriminalization laws were linked to each adolescent in the sample based on the state and year of the survey. As most states conduct the surveys in the spring (3,24), adolescents were coded as living in a state with MML or decriminalization if their state had enacted the law prior to April of the cycle year. For both MML and decriminalization laws, we created three sets of variables to be used in separate models to assess effects of policy enactment, length of exposure to policy, and an aspect of policy leniency. First, in each year we defined a binary indicator variable equal to one if the state had enacted the law and equal to zero otherwise. Second, we created continuous variables equal to the number of years since the enactment of MML and since the enactment of decriminalization (with nonenactors coded as zero). Third, to address one aspect of the leniency versus restrictiveness of the policies, following prior research (1) we generated a dichotomous indicator equal to one if the medical marijuana law allowed possession of more than 2.5 ounces, and an indicator for whether the number of ounces decriminalized was greater than 1, with a more strict policy or no policy coded as zero.

Individual and contextual covariates

Adolescents reported on their age (coded categorically as 14, 15, 16, 17, 18+ years) and sex (female, male). We combined self-reports of ethnicity and race to create a four-category variable of race/ethnicity (non-Hispanic white, non-Hispanic Black, Hispanic, non-Hispanic other). No additional socio-demographic information on the students or families was collected in the YRBS consistently across states and years. Due to strong co-occurrence of marijuana and tobacco use among teens and evidence that early tobacco use presages use of marijuana in adolescence (26), we also included adolescent reports of current cigarette use (a dichotomous indicator of whether adolescents had smoked cigarettes in the prior 30 days) as an individual covariate.

Contextual covariates, like the primary policy variables of interest, were coded at the state level as time-varying. Specifically, we used average cigarette taxes (in 2015 dollars) from the first quarter of each year (27), 100% smoke-free restaurant legislation from the American Nonsmokers' Rights Foundation [28], which we used as proxy for state smoke-free policies [29], beer taxes (in 2015 dollars) [30], which are used as proxy for the price of alcohol [31], and the state unemployment rate [32]. We also included state and year indicators.

Statistical analysis

Our primary analyses investigated links between MML and decriminalization policies and adolescent marijuana use using difference-in-differences models, an analytic technique that compares changes in outcomes over time in states that enacted the policy and states that did not (9). Equation 1 presents an exemplar logistic regression equation.

$$Pr[y_{ist} = 1] = \gamma \mathrm{MML}_{st} + \lambda \mathrm{Decrim}_{st} + \beta_1 \mathrm{X_i} + \delta_s + \theta_t \quad (1)$$

where y_{ist} is the binary indicator for marijuana use by individual i in state s and year t, X_i is a vector of individual characteristics, δ_s is a vector of state characteristics and state fixed effects (e.g., indicator

variables for each of 44 states with one omitted), and θ_t denotes year fixed effects (indicator variable for each of 8 years with one omitted). The parameters γ and λ capture the difference-in-differences effect of the medical marijuana and decriminalization laws. This model, an extension of simpler difference-in-differences models which assess a shift at a single time-point, is a rigorous method of exploiting changes in policy domains across multiple states and years, and has been used extensively in other research comparing policy shifts across states over time (33,34). Subsequently, we included interactions between both MML and decriminalization laws and individual sociodemographic characteristics (age, race/ethnicity, and sex), including all interactions together. All models included controls for individual (age, race/ethnicity, sex, and current cigarette smoking) and contextual characteristics (state-level beer and cigarette taxes, smoke-free policies, and unemployment rate), as well as year and state fixed effects.

Analyses were conducted using Stata statistical software, version 14.2 (StataCorp, College Station, TX). We accounted for the complex sample design by including survey weights, which provide representative estimates for the 45 states included in the analysis. The weights adjust for nonresponse as well as oversampling of Black and Hispanic adolescents and are based on students' sex, race/ethnicity, and school grade (17). Multiple-year adjustment was applied to survey weights (10). For each regression, we report odds ratios and confidence intervals, as well as average marginal effects and predicted probabilities (for dichotomous predictor variables).

Results

Descriptive data on marijuana policies and use

Among the 45 states included in the analysis (Table 1), 11 states enacted a marijuana decriminalization law, and 18 states enacted a MML by April 2015. Considering patterns across states (Table 2), we find notable variability in the timing and ordering of policy enactment. For example, of the 10 states which had enacted both decriminalization and MML policies by 2015, 6 enacted decriminalization first whereas 2 enacted a MML policy first and an additional 2 enacted both in the same year (1 concurrently and another in which a MML preceded decriminalization by just a few months). Yet eight states had enacted a MML without a decriminalization policy, whereas only two had enacted decriminalization without a MML. Finally, 25 states had not enacted either policy prior to the 2015 YRBS survey. These trends indicate both that there is not a normative pattern of enacting one law prior to the other, and that there is notable variability across states in the timing and ordering of enactment which is key for modeling effects of state policy shifts. Importantly, the prevalence of marijuana use also varied notably across states, with the mean weighted prevalence of use across survey years ranging from 8.6 percent in Utah to 26.9 percent in Vermont (Table 1).

Table 2. Order of Medical Marijuana and Decriminalization Law Passage.

Law Passage	States
Passed Both MML & Decriminalization Laws	
MML Passed First	DE, VT
Decriminalization Passed First	AK, CA, CT, MA, ME, NY
MML & Decriminalization Passed concurrently	MD, NV
Passed MML Only	AZ, IL, MI, MT, NH, NJ, NM, RI
Passed Decriminalization Law Only	OH, OK
No MML or Decriminalization Laws Passed	AL, AR, FL, GA, IA, ID, IN, KS, KY, LA, MO, MS, NC, ND, NE, PA, SC, SD, TN, TX, UT, VA, WI, WV, WY

Preparatory models to delineate primary model specification

Prior to presenting our main models, we discuss results from model specifications which were used to delineate and justify our modeling strategy. The first analysis addressed whether the data met the key assumption of parallel trends – that is, the assumption that, sans new marijuana policies, adolescent marijuana use would have trended similarly in states that did and did not enact such policies. To test this assumption, we created a set of 6 binary lead indicators to delineate being less than 1 year, 1 year, 2 years, 3 years, 4 years, or 5 or more years prior to enacting each law. The referent category for these variables was having not enacted the law. We then estimated a variant of Equation 1 which included this set of six lead indicators for both MML and decriminalization policies in addition to the enactment indicators and all covariates. Using this rigorous modeling approach, results (Supplementary Table 2) indicate no significant differences between states which did or did not enact MML policies in the 5+ years prior to enactment. For decriminalization, five of the six lead variables were nonsignificant, although in the second year prior to enrollment, adolescents in states which would enact decriminalization had a 17.8 percent lower odds of marijuana use in the past month than did adolescents in states which did not enact a decriminalization law. Translated into predicted probabilities, these odds suggest a predicted probability

of 17.9 percent use in states which enacted decriminalization two years later versus 19.7 percent in states which did not. Together, these results provide strong evidence that there were no differences in marijuana use across states that did and did not enact MML, and limited evidence of any differences in use across states which did and did not enact decriminalization policies, supporting the use of our difference-in-differences modeling strategy.

A second initial specification estimated a zero-inflated negative binomial model with the dichotomous indicators of MML and decriminalization enactment (along with all covariates) to assess whether marijuana policies were associated with adolescents' frequency of marijuana use. Results (Supplementary Table 3) show significant associations between marijuana policies and the structural zeroes in the logistic component of the model but no significant associations with the count response. In a third initial specification model we estimated a logistic regression model using dichotomous policy enactment indicators to predict the indicator of heavy marijuana use (Supplementary Table 4), finding no evidence for associations between marijuana policies and heavy marijuana use. We take this as evidence that policies are linked with decisions to use versus not to use marijuana, but not with the frequency of use. Hence, we focus our main analyses on logistic regression models predicting any current marijuana use.

MML and decriminalization enactment and adolescent marijuana use

Table 3 presents results from our main difference-in-differences models using the dichotomous marijuana policy enactment variables to predict current marijuana use. Results indicate that the enactment of a MML was associated with a significant *reduction* in current marijuana use, whereas no significant effects of decriminalization emerged for the sample as a whole. In these rigorous models adjusting for adolescent characteristics, other substance use policies, and state and year fixed effects, enactment of a MML led to small differences: adjusting for other factors, predicted probabilities of marijuana use were 18.9 percent in states which had enacted a MML compared to 20.0 percent in states which had not.

In relation to covariates, results suggest that other state policy and macroeconomic factors also were associated with adolescent marijuana use, with each dollar of beer taxes associated with a 55.6 percent lower odds of marijuana use, and each percentage point in the unemployment rate associated with a 2.5 percent higher odds of use. In relation to individual covariates, results suggest that marijuana use was lower among younger adolescents but rose quickly in the early years of high school, with predicted probabilities rising from 13.5 percent among 14-year-olds to 17.3 percent among 15-year-olds and then rising again and remaining between 21 and 22 percent for 16-year-olds and above. Race/ethnicity was also significantly associated with use, with Black adolescents having notably higher predicted probabilities of use, at 25.9 percent, than their white counterparts, at 18.6 percent, the latter of which showed similar rates to Hispanic and other racial/ethnic groups. Males had significantly higher predicted probabilities of use (21.1 percent) than females (18.4 percent). The biggest difference emerged in relation to current cigarette smokers (61.1 percent versus 11.6 percent).

MML and decriminalization enactment effects across age, race/ethnicity, and gender subgroups

Table 4 present results from interactions between MML and decriminalization policies and adolescent characteristics, showing the overall significance of each set of interactions (Wald test), the odds ratios and confidence intervals of the interaction terms, as well as the marginal effects for each subgroup, indicating whether MML or decriminalization was associated with a significant shift in marijuana use among each subgroup of adolescents. Results revealed mixed evidence of differential effects of MML enactment on marijuana use across age, race/ethnicity, or gender subgroups. Although the interactions with age and race/ethnicity were not significant, results indicate that MML enactment was associated with a small significant 1.8 percentage point reduction in marijuana use among 15 year olds, with nonsignificant shifts among other age groups. MML enactment was significantly related to lower marijuana use among Black and Hispanic adolescents, who had 3.9 percentage point and 2.7 percentage point decreases, respectively, in marijuana use after the enactment of a MML in comparison to nonsignificant shifts among white youth and those of other race/ethnicities. The interaction between MML and sex was significant, with MML more negatively linked to use among males, who showed a significant 2.7 percentage point reduction in current marijuana use, than among females, who showed a nonsignificant 0.3 percentage point increase in use following MML enactment.

Considering decriminalization, significant interactions emerged with age and race/ethnicity. The enactment of a decriminalization law was associated with a 1.7 percentage point decrease in current marijuana use among 14-year-olds that was significantly different from

Table 3. Main effects of difference-in-differences logistic regression models of marijuana policy enactment and current marijuana use: Youth Risk Behavior Survey 1999–2015 (N = 861,082).

	OR[a] (95% CI)	Marginal effect of coefficient[b] (SE)	Predicted Probabilities
Medical Marijuana Law			
No	1.000 Referent	0.000 Referent	0.200
Yes	**0.911 (0.850–0.975)**	**−0.011 (0.004)**	**0.189**
Decriminalization			
No	1.000 Referent	0.000 Referent	0.197
Yes	1.011 (0.934–1.094)	0.001 (0.005)	0.198
Age			
14	1.000 Referent	0.000 Referent	0.135
15	**1.439 (1.335–1.550)**	**0.038 (0.004)**	**0.173**
16	**1.979 (1.837–2.131)**	**0.077 (0.004)**	**0.212**
17	**2.117 (1.948–2.301)**	**0.086 (0.005)**	**0.221**
18	**2.048 (1.889–2.221)**	**0.082 (0.005)**	**0.216**
Race			
White	1.000 Referent	0.000 Referent	0.186
Black	**1.742 (1.630–1.862)**	**0.073 (0.004)**	**0.259**
Hispanic	1.080 (0.956–1.221)	0.009 (0.007)	0.195
Other	1.025 (0.891–1.178)	0.003 (0.008)	0.188
Sex			
Female	1.000 Referent	0.000 Referent	0.184
Male	**1.241 (1.180–1.306)**	**0.027 (0.003)**	**0.211**
Current Smoker			
No	1.000 Referent	0.000 Referent	0.116
Yes	**13.223 (12.556–13.926)**	**0.318 (0.003)**	**0.611**
Smoke Free Restaurant			
No	1.000 Referent	0.000 Referent	0.194
Yes	1.051 (0.991–1.116)	0.006 (0.004)	0.200
Beer Taxes	**0.544 (0.307–0.964)**	**−0.075 (0.036)**	
Cigarette Taxes	1.030 (0.992–1.069)	0.004 (0.002)	
Unemployment Rate	**1.025 (1.005–1.045)**	**0.003 (0.001)**	

Values in bold type are statistically significant ($p \leq .05$)
CI = confidence interval; OR = odds ratio; SE = standard errors
[a]Model includes adjustment for year and state
[b]Weighted

Table 4. Interaction effects of difference-in-differences logistic regression models of marijuana policy enactment and current marijuana use: Youth Risk Behavior Survey 1999–2015 (N = 861,082).

	OR[a] (95% CI)	Marginal effect of coefficient[b] (SE)	Wald Test P-Value
MML X Age			0.711
14	1.000 Referent	−0.013 (0.007)	
15	0.995 (0.810–1.223)	**−0.018 (0.008)**	
16	1.108 (0.918–1.337)	−0.009 (0.007)	
17	1.105 (0.892–1.371)	−0.009 (0.009)	
18	1.130 (0.917–1.391)	−0.008 (0.011)	
MML X Race/ethnicity			0.159
White	1.000 Referent	0.001 (0.007)	
Black	0.742 (0.542–1.016)	**−0.039 (0.016)**	
Hispanic	0.811 (0.633–1.040)	**−0.027 (0.012)**	
Other	0.947 (0.772–1.162)	−0.008 (0.010)	
MML X Sex			**0.001**
Female	1.000 Referent	0.003 (0.006)	
Male	**0.785 (0.678–0.910)**	**−0.027 (0.006)**	
Decriminalization X Age			**0.017**
14	1.000 Referent	**−0.017 (0.006)**	
15	1.146 (0.978–1.344)	−0.006 (0.007)	
16	**1.285 (1.106–1.496)**	0.008 (0.007)	
17	**1.206 (1.022–1.422)**	−0.001 (0.008)	
18	**1.301 (1.091–1.552)**	0.010 (0.010)	
Decriminalization X Race/ethnicity			**<0.001**
White	1.000 Referent	**0.016 (0.006)**	
Black	0.848 (0.706–1.018)	−0.004 (0.011)	
Hispanic	**0.711 (0.575–0.879)**	**−0.026 (0.012)**	
Other	**0.628 (0.509–0.775)**	**−0.044 (0.012)**	
Decriminalization X Sex			0.979
Female	1.000 Referent	−0.001 (0.006)	
Male	0.999 (0.901–1.107)	−0.000 (0.006)	

Values in bold type are statistically significant ($p \leq .05$)
CI = confidence interval; OR = odds ratio; SE = standard errors
[a]Model includes adjustment for the following covariates: age, race/ethnicity, sex, current tobacco use, year, state, beer taxes, cigarette taxes, smoke free policies, and unemployment rate, as well as MML and decriminalization.
[b]Weighted

the nonsignificant shifts among youth aged 16, 17, and 18. Moreover, decriminalization was associated with a 1.6 percentage point increase in marijuana use among white adolescents, but with 2.6 and 4.4 percentage point decreases in use among Hispanic adolescents and those who reported as other race/ethnicity, respectively.

Testing the robustness of results

Following our main models we ran a series of sensitivity analyses to test the robustness of results. The first sets assessed length of exposure to marijuana policies, with the first model using a continuous measure of years since enactment of MML and decriminalization to test linear effects (with non-enactors coded as 0; Table 5, top panel) and the second using nonlinear categorical variables delineating whether states were within 5 years, between 5 and 10 years, or more than 10 years after enactment (in comparison to having not enacted; Table 5, bottom panel). The linear length of exposure to marijuana policies model found that every additional year of MML exposure decreased the odds of marijuana use by 2.0 percent, whereas no significant effect emerged of length of exposure to decriminalization. Nonlinear models generally replicated these patterns. Specifically, results show a small negative effect of MML enactment within the first 5 years, leading to a predicted 18.7 percent probability of marijuana use, which stayed at a similarly significant negative effect 5 to 10 years after enactment (predicted probability of 18.4 percent), and then grew more substantially after 10 years, leading to a predicted 16.1 percent probability of use. Decriminalization, on the other hand, showed no significant association with adolescent marijuana use for the first 10 years, although results identified a significant increase in use of marijuana 10 or more years after enactment of decriminalization laws, with a predicted probability of use rising to 22.1 percent.

As a final robustness check we assessed one aspect of the permissiveness of marijuana policies, considering the amount of marijuana allowed under MML and decriminalization policies, similar to prior work (1). Results of MML policies allowing more than 2.5 ounces of marijuana (Table 6) were similar to those from the main effects model in Table 3, suggesting that the amount of marijuana allowed under the law does not significantly alter the size of its effect. Specifically, exposure to a more permissive policy was associated with a 1.2 percent point decrease in marijuana use, from 20.0 to 18.8 percent. In contrast, no main effects emerged in response to exposure to policies decriminalizing more than 1 ounce of marijuana.

Discussion

Recent decades have seen substantial liberalization of marijuana laws in states across the U.S., starting with decriminalization efforts, followed by legalization of marijuana use for medicinal purposes, and more recently encapsulating full recreational legalization initiatives, with such laws consistently focused on adults aged 21 and above. Although adolescents are not directly targeted, nonetheless access and signaling theories argue that such policies may increase access to marijuana and decrease perceptions of harm, thus leading to positive impacts on adolescent use of marijuana (8,9).

Taking advantage of the natural experiment created by diversity in the timing and enactment of medical marijuana and decriminalization policies across states and implementing rigorous quasi-experimental analytic techniques, we found mixed evidence for these arguments. The enactment of MMLs was associated with small significant decreases in the likelihood of current marijuana use among high school-age adolescents. These results replicate and extend those of Johnson and colleagues (1) and Hasin and colleagues (15), which also used large school-based samples, by including more recent cohorts, by controlling for marijuana decriminalization and other substance policy shifts, and by showing that negative links between MML and adolescent marijuana use are primarily concentrated in the subpopulations showing the highest rates of use as well as the highest legal repercussions: males and adolescents of color. The size of these associations, while small overall, vary across subgroups, with effects of notable practical significance among subgroups at highest risk. Decreases in marijuana use among males and Hispanic and Black youth, for example (2.7, 2.7, and 3.9 percentage point declines, respectively), were of a similar or larger magnitude as the male-female population level difference in use (2.7 points).

Although we did not have data to identify mechanisms underlying these shifts, one hypothesis is that MMLs may signal that marijuana has a medicinal rather than recreational purpose (15). Indeed, some research has found that perceptions of harm from marijuana *increased* among some subgroups of adolescents following enactment of MML (11). Other scholars have further suggested that the enactment of more liberal marijuana laws may have increased parental oversight regarding adolescent behaviors (15), in turn decreasing use, both important hypotheses to consider in future research. Although our results are promising in suggesting that youth are not increasing entry into marijuana use in response to MMLs, it is important to note that no associations emerged in relation to the

Table 5. Difference-in-differences logistic regression models of current marijuana use with years of exposure to marijuana policy: Youth Risk Behavior Survey 1999–2015 (N = 861,082).

	OR[a] (95% CI)	Marginal effect of coefficient[b] (SE)	Predicted Probabilities
Linear Years Since Enactment			
MML Years of Exposure	**0.980 (0.968–0.992)**	**−0.003 (0.001)**	
Decriminalization Years of Exposure	1.007 (0.995–1.019)	0.001 (0.001)	
Categorical Years Since Enactment			
MML: ≤ 5 years			
No	1.000 Referent	0.000 Referent	0.198
Yes	**0.909 (0.848–0.974)**	**−0.012 (0.004)**	**0.187**
MML: 5–10 years			
No	1.000 Referent	0.000 Referent	0.197
Yes	**0.891 (0.801–0.992)**	**−0.014 (0.007)**	**0.184**
MML: >10 years			
No	1.000 Referent	0.000 Referent	0.206
Yes	**0.681 (0.594–0.781)**	**−0.047 (0.009)**	**0.161**
Decriminalization: ≤ 5 years			
No	1.000 Referent	0.000 Referent	0.197
Yes	1.012 (0.935–1.095)	0.001 (0.005)	0.199
Decriminalization: 5–10 years			
No	1.000 Referent	0.000 Referent	0.197
Yes	1.020 (0.881–1.182)	0.003 (0.009)	0.200
Decriminalization: >10 years			
No	1.000 Referent	0.000 Referent	0.189
Yes	**1.281 (1.028–1.597)**	**0.031 (0.014)**	**0.221**

Values in bold type are statistically significant ($p \leq .05$)
CI = confidence interval; OR = odds ratio; SE = standard errors
[a]Models include adjustment for the following covariates: age, race/ethnicity, sex, current tobacco use, year, state, beer taxes, cigarette taxes, smoke free policies, and unemployment rate.
[b]Weighted

Table 6. Difference-in-differences logistic regression models of current marijuana use with ounces allowed in marijuana policy: Youth Risk Behavior Survey 1999–2015 (N = 861,082).

	OR[a] (95% CI)	Marginal effect of coefficient[b] (SE)	Predicted Probabilities
MML > 2.5 Ounces			
No	1.000 Referent	0.000 Referent	0.200
Yes	**0.908 (0.850–0.970)**	**−0.012 (0.004)**	**0.188**
Decriminalization > 1.0 Ounces			
No	1.000 Referent	0.000 Referent	0.197
Yes	1.022 (0.933–1.120)	0.003 (0.006)	0.199

Values in bold type are statistically significant ($p \leq .05$)
CI = confidence interval; OR = odds ratio; SE = standard errors
[a]Models include adjustment for the following covariates: age, race/ethnicity, sex, current tobacco use, year, state, beer taxes, cigarette taxes, smoke free policies, and unemployment rate.
[b]Weighted

frequency of marijuana use or heavy use, suggesting that youth who use on a regular basis may be impervious to such policy signals.

Other studies using a different data source (with household-based sampling and coverage of all 50 states) as well as different modeling strategies have found nonsignificant (8) or positive (19) links between MML enactment and adolescent marijuana use, although we note that in practical terms, differences in results are small. Further, as noted by Johnson and colleagues (1), these studies did not adjust for individual state fixed effects or other related policy shifts, and hence may have misspecified the effect of MML enactment. In addition to sampling and modeling strategies, other reasons for inconsistencies across studies abound, including inclusion of different ages, years, and states, as well as differences in the operationalization of both policy indicators and marijuana use outcomes (33). These inconsistencies in results across studies suggest the need for replicating exact model specifications across datasets to further explore whether small differences in results are due to population or sampling differences, to model specifications and covariates, or perhaps to other reasons.

In contrast to the protective effects of MMLs, decriminalization policies showed smaller and more mixed links to adolescent marijuana use. Although not significantly associated with marijuana use among the population of high school students as a whole, decriminalization appeared to function as a deterrent to adolescent marijuana use among some subpopulations, including younger adolescents and those of Hispanic and other ethnicities, but was linked with small yet statistically significant increases in the likelihood of marijuana use

among white adolescents and with larger growth in use when adolescents had been exposed to decriminalization for the majority of their lives (more than 10 years). These patterns are reflective of the mixed findings in the literature as a whole (12,13). In their analysis of YRBS data from 1995 through 2011, Ammerman et al. found that links between decriminalization legislation and adolescent marijuana use differed slightly from state to state, though results were generally not significant (13). Similarly, Miech et al. found cohort effects such that decriminalization legislation had small positive associations with 12th grade students' likelihood of marijuana use, but non-significant links for 8th and 10th grade students (12).

As with medical marijuana laws, the lack of connections between decriminalization laws and the frequency of marijuana use or heavy use suggests that policy responses are concentrated among adolescents exploring or initiating marijuana use rather than among heavy users. Similarly, policies which allow greater amounts of marijuana were not differentially influential for adolescents' likelihood of use. Nonetheless, these results might suggest that laws reducing penalties for marijuana use may ease concerns and decrease legal deterrents to accessing marijuana among some youth, suggesting in turn that new policies legalizing recreational marijuana may have similar and even stronger results. State laws legalizing recreational marijuana use have now passed in nine states and the District of Columbia. Studies on the first two implementers, Colorado and Washington, found small, often nonsignificant increases in adolescent use of marijuana following recreational marijuana legalization (35). It is unfortunate that states with the earliest implementation of recreational marijuana are not included in the YRBS data (Colorado, Washington, Oregon, and, until 2015, California), which prohibited consideration of these new laws in the current analysis. Pre- and postpolicy implementation data across multiple states have not yet been released. In the meantime, continued efforts to decrease adolescent entry into and escalation of marijuana use remain key public health concerns.

Moreover, as trends in substance use evolve over time, it is essential for further research to explore connections across various substance policy levers and substance use. One of the innovations of this work was consideration of the effects of alcohol and tobacco policies on marijuana use, finding that increased beer and cigarette taxes and smoke-free legislation did not lead to a substitution to marijuana among adolescents; rather, increased beer taxes were associated with reductions in marijuana use (whereas rising unemployment was linked to increases in use). Still, the notable connection between tobacco and marijuana use among adolescents suggests the importance of additional research to delineate whether marijuana policies affect use of diverse tobacco products, or whether other tobacco policies, such as those increasing eligibility to adults age 21 and above, may affect marijuana use. Links between marijuana use and the growing market of prescription and street opioids is another key concern for future research.

In closing, it is essential to highlight limitations of this work, including reliance on self-reports of marijuana use which may be biased; exclusion of high school dropouts, a particularly high-risk group (36); lack of information on how adolescents access marijuana and their knowledge and understanding of marijuana policies; and omission of some states which have been leaders in marijuana policy shifts. Derived from a natural (rather than randomized) experiment, it is also possible that unmeasured factors biased our results. As we await data necessary to assess the effects of emerging marijuana legalization policies, these results suggest that prior policy shifts liberalizing marijuana access and penalties have shown, on balance, limited risk for adolescents.

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Conflicts of interest

None of the authors have any potential, perceived, or real conflicts of interest or financial conflicts.

Disclaimer

The results and conclusions reported are those of the researchers and not the Departments of Health of the states providing data.

List of Abbreviations

MML medical marijuana laws
YRBS youth risk behavior survey

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