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Research Article

Insufficient Sleep Correlates with the Natural Environment, Health Behaviors, and Selected Causes of Death

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Abstract

Objective: *To estimate the prevalence of insufficient sleep in the contiguous US and show how insufficient sleep correlates with selected natural environment factors, health behaviors, and causes of death.*

Design: *An ecologic study design was used with measurements for each variable on the county level. Setting: A total of 3,108 counties in the contiguous US.*

Measures: *Measurements were on the county level, which included altitude, sunlight, ambient air temperature, PM2.5, and precipitation, and selected health behaviors and causes of death.*

Results: *Higher altitude is associated with better sleep, but this association is explained by lower average daily fine particulate matter, maximum air temperature, and precipitation at higher altitude. Improved sleep duration correlates with less air pollution, moderate sleeping temperatures, and less precipitation, which likely correlates with better health behaviors. Sufficient sleep may further improve by lower tobacco smoking, obesity, physical inactivity, and better diet. After accounting for the environmental and health behavior variables, insufficient sleep no longer had a direct effect on the causes of death, except for injury and motor vehicle accidents.*

Conclusions: *Better sleep duration occurs at lower altitude and in places where there is less average daily fine particulate matter, more moderate maximum air temperature, and lower precipitation. Better sleep duration also correlates with less tobacco smoking, obesity and physical inactivity, and better diet. After accounting for the environmental and health behavior variables, insufficient sleep continues to have a direct influence on death, except rates associated with injury and motor vehicle accidents.*

Keywords: Sleep, Altitude, Sunlight, Ambient Air Temperature, PM2.5, Precipitation, Health Behaviors, Mortality

Introduction

Research has identified that individuals with insufficient sleep (circadian rhythm disorders) are at greater risk for cardiovascular disease, cancer, diabetes, Alzheimer's, and respiratory infections [1-11]. The relationship between suicide and sleep disturbances is also well studied in the literature [12-14]. The relationship between traffic, injury, and work accidents and insufficient sleep has also been documented [15, 16]. Given that the quality of sleep is a modifiable risk factor, it is an important area of study for reducing several serious health problems and related deaths.

Scientists have concluded that adults require 7 or more hours of sleep per 24-hour period to experience the best health and quality of life [17]. In a report from the Centers for Disease Control and Prevention based on results from the Behavior Risk Factor Surveillance System (BRFSS), short sleepers were more likely to experience 10 chronic health conditions, including coronary heart disease, cancer, diabetes, and depression [18]. The survey also identified adults who were short sleepers as being more likely to be current smokers, obese, and physically inactive. Geographic maps of areas with short sleep duration show considerable variation across the United States, implicating natural environmental factors as possible correlates.

The purpose of the current study was to identify the extent to which the prevalence of insufficient sleep in the contiguous US is associated with natural environmental factors (altitude, sunlight, ambient air temperature, PM2.5, and precipitation), as well as selected health behaviors and causes of death. The strength of the association between insufficient sleep and the causes of death will be estimated and compared among the other health behaviors after adjusting for the environmental factors.

Methods

The current study uses an ecologic study design to assess the association between insufficient sleep and selected natural environment factors and health behavior. Measurements for each variable are on the county level, with 3,108 counties in the contiguous US represented in the analysis.

Sleep Variable

County-level % insufficient sleep is based on data from the BRFSS survey, 2016. The BRFSS is a nationally represented annual survey conducted among adults in the United States [19]. Insufficient sleep is defined as less than 7 hours of sleep per 24-hour period [17]. Determination of sufficient sleep was based on the question: "On average, how many hours of sleep do you get in a 24-hour period?"

Health Behavior Variables

County-level health behavior data were compiled by a Robert Wood Johnson Foundation program called County Health Rankings & Reports: Building a Culture of Health, County by County, representing different sources and time periods [20]. Health behavior variables considered in this study were: % adult smokers, % adult obesity, % physically inactive, and Food Environment Index (0, worst to 10, best). The % of adults who currently smoke was obtained from the BRFSS, 2017. The % of adult obesity and the % physically inactive were obtained from the United States Diabetes Surveillance System, 2016. The Food Environment Index was obtained from Map the Meal Gap, 2017, and USDA Food Environment Atlas, 2015.

Natural Environment Variables

The natural environmental variables include weighted altitude (m), average daily sunlight (KJ/m2), average daily maximum air temperature (F), average fine particulate matter (ug/m3), and average daily precipitation (mm). County-level natural environmental data were available through the Environmental Public Health Tracking Network, the United States Geological Survey's National Elevation Dataset programs and the Wonder Online Databases supported by the Centers for Disease Control and Prevention, which they obtained from the North American Land Data Assimilation System [20-23].

Weighted altitude in meters above sea level was estimated for each county. Altitude was weighted to provide a measure of altitude that represents where most people in the county live. This is particularly an issue for some mountainous areas where people tend to live in the valleys. Weighted altitude has been used in a previous study relating altitude to suicide [24]. Average county-level daily sunlight, maximum air temperature and precipitation represent the combined years 2007-2011. These data were obtained through the North American Land Data Assimilation System, available through the CDC Wonder database [CDC WONDER [Internet] [22]. Average county-level daily density of fine particulate matter in micrograms per cubic meter (PM2.5) cover 2011-2014, obtained from the Environmental Public Health Tracking network [23].

Cause of Death Variables

Mortality rates for specific causes were obtained from the National Center for Health Statistics, 2013-2017 [25]. Cause of death was coded according to the 10th revision of the International Statistical Classification of Diseases and Related Health Problems (ICD-10) [26]. The following causes of death are considered in this study: all causes, heart disease, cerebrovascular disease, tobacco-related cancers (oral cavity and pharynx, esophagus, stomach, pancreas, respiratory system, cervix uteri, urinary bladder, and kidney and renal pelvis), non-tobacco-related cancers, diabetes, Alzheimer's disease, pneumonia/influenza, injury, and motor vehicle. Rates were age-adjusted to the 2000 US population [27]. Rates represent individuals aged 40 years and older, except for all causes, injury, and motor vehicle, which represent all ages. No ethical approval was sought or required for this study, which used publicly available datasets.

Statistical Techniques

Summary statistics were computed for % insufficient sleep and the natural environmental, health behavior, and mortality rate variables. First, regression analysis estimated the association between % insufficient sleep and the natural environment, health behavior and mortality rate data. Second, simple and multiple regression models were then used to estimate mean scores and mean differences in % insufficient sleep for the counties according to levels of altitude. Adjustment was made for the other natural environmental variables. Third, linear and second-order polynomial models were used to fit the associations between altitude and average daily sunlight, maximum air temperature, PM2.5, and precipitation. Fourth, multiple regression models estimated the association between the cause-specific mortality rates and % insufficient sleep, adjusting for the environmental and health behavior variables. Statistical significance was based on two-sided hypothesis tests at the 0.05 level. Statistical analyses were performed using SAS 9.4 (SAS Institute, Cary, NC, USA, 2012). Graphs were created in Microsoft Excel, 2016.

Results

Mean % insufficient sleep (< 7 hours of sleep per 24-hour period) across in the counties in the contiguous United States is 33.04% (SD = 4.17), with the median 33.0%, minimum 23.0% and the maximum 47.0%. County-level mean estimates for selected variables are shown in (Table 1), along with univariate regression estimates of the association between % insufficient sleep and selected environmental and health behavior factors and cause-specific death rates. Percent insufficient sleep is negatively associated with higher altitude increases, but positively associated with higher average daily sunlight, maximum air temperature, PM2.5, and precipitation increase. Percent insufficient sleep is positively associated with % smokers, % physically inactive, and % adults with obesity increase, but negatively associated with the food environment. Percent insufficient sleep is most strongly correlated with % smoking. There is a positive association between % insufficient sleep and the selected causes of death. Insufficient sleep has the greatest effect on heart disease and tobacco-related cancer.

Table 1 Summary statistics and regression estimates of % insufficient sleep and the environmental, health behavior, and causes of death variables

	No.	Mean	Standard Deviation	Slope Estimate	Standard Error	F Value	Pr > F	R-Square %
Environmental Variables								
Weighted Altitude (m)	3106	414.32	487.36	-0.0038	-0.0001	750.07	<.0001	19.46
Average Daily Sunlight (KJ/m²)	3106	16398	1605	0.0004	0.0000	82.50	<.0001	2.59
Average Daily Max Air Temperature (F)	3106	65.38	9.28	0.1793	0.0074	589.81	<.0001	15.97
Average Daily PM2.5	3108	9.02	1.97	1.1410	0.0320	1270.02	<.0001	29.02
Average Daily Precipitation (mm)	3106	2.72	0.91	2.2057	0.0722	934.32	<.0001	23.14
Health Behaviors								
% Smokers	3108	17.44	3.57	0.7491	0.0161	2177.32	<.0001	41.21
% Physically Inactive	3108	27.47	5.70	0.3141	0.0119	702.39	<.0001	18.44
% Adults with Obesity	3108	32.90	5.43	0.3022	0.0127	570.59	<.0001	15.52
Food Environment Index 0 (worst) – 10 (best)	3089	7.46	1.13	-1.0471	0.0639	268.91	<.0001	8.01
Age-adjusted Mortality Rate								
All Cause	3105	818.72	147.72	0.0152	0.0004	1274.11	<.0001	29.11
Heart Disease (Aged 40+)	3083	427.74	109.94	0.0179	0.0006	898.09	<.0001	22.57
Tobacco-related Cancer (Aged 40+)	3031	183.40	41.72	0.0467	0.0016	868.36	<.0001	22.28
Non Tobacco-related Cancer (Aged 40+)	3049	205.83	31.85	0.0366	0.0023	262.42	<.0001	7.93
Cerebrovascular Disease (Aged 40+)	2894	93.92	24.48	0.0507	0.0030	295.04	<.0001	9.26
Diabetes (Aged 40+)	2727	58.43	27.09	0.0373	0.0027	185.36	<.0001	6.37
Pneumonia/Influenza (Aged 40+)	2544	40.18	16.97	0.0435	0.0045	92.59	<.0001	3.51
Alzheimer's (Aged 40+)	2749	73.95	31.29	0.0082	0.0025	11.25	0.0008	0.41
Injury	3015	86.63	25.11	0.0134	0.0030	20.37	<.0001	0.67
Motor Vehicle	2688	19.02	9.31	0.0535	0.0081	43.56	<.0001	1.60

Note: R^2 is a measure of the proportion of the variance for a dependent variable that is explained by an independent variable or variables within a regression model. Tobacco-related cancers consist of oral cavity and pharynx, esophagus, stomach, pancreas, respiratory system, cervix uteri, urinary bladder, and kidney and renal pelvis.

The negative association between altitude and % insufficient sleep may be because of altitudes association with other environmental variables. Slope estimates of the association between weighted altitude and average daily sunlight, maximum air temperature, PM2.5, and precipitation are shown in (Figure 1). A linear relationship shows a positive association between altitude and sunshine and a negative association between altitude and temperature. A second-order polynomial model provides a better fit to the associations involving altitude and PM2.5 and altitude and precipitation. Average daily PM2.5 decreases with higher altitude through about 2500 meters and then is flat. Average daily precipitation decreases with higher altitude through about 2000 meters and then increases with higher altitude.

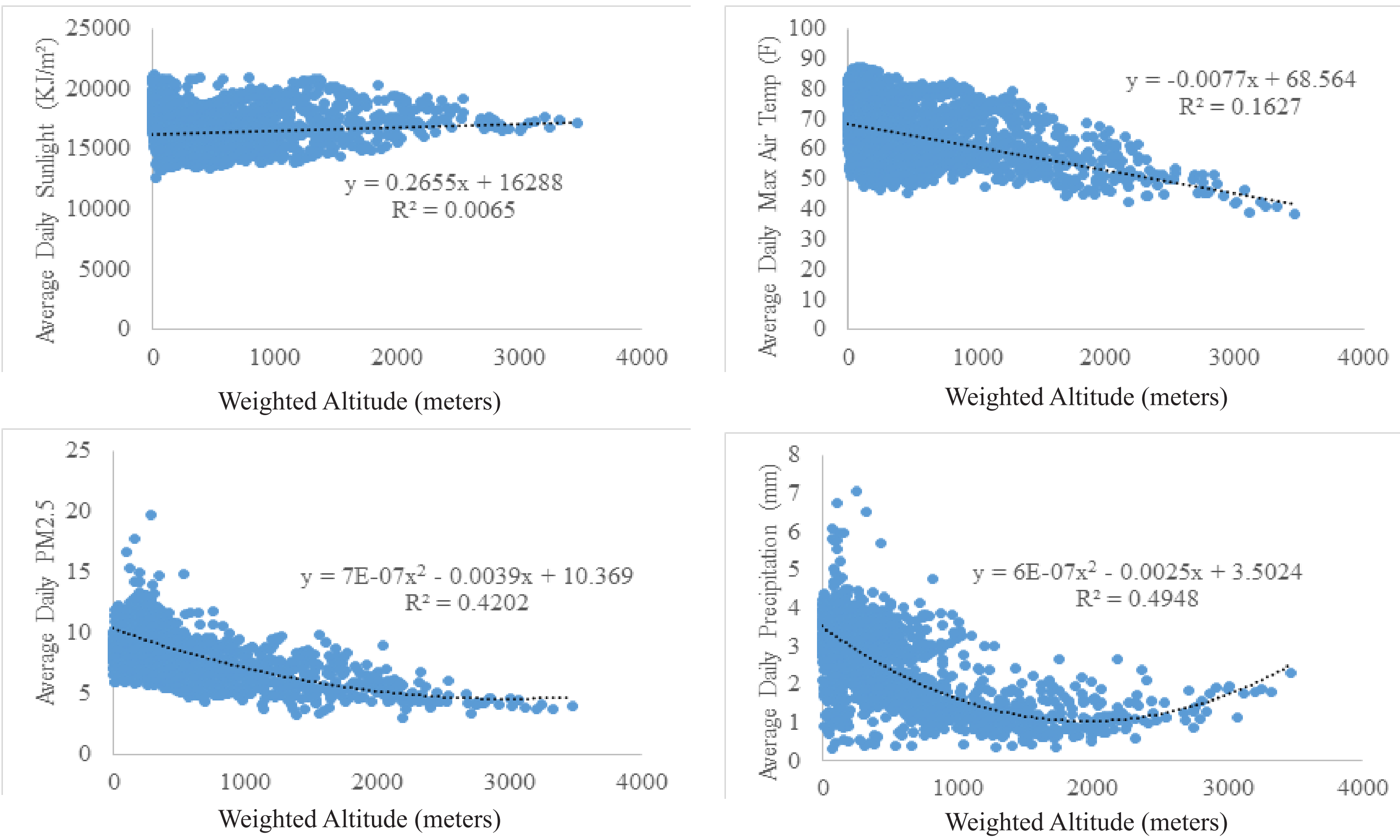

Figure 1 Association between altitude and the other environmental variables (average daily sunlight, maximum air temperature, PM2.5, and precipitation)

In a multiple regression model where % insufficient sleep was regressed on each of the natural environmental variables, altitude became insignificant (Pr > F = 0.3487) (Table 2). Each of the remaining variables positively correlate with % insufficient sleep, with 37.85% of the variation in the sleep variable explained by average daily PM2.5, maximum air temperature, precipitation, and sunlight.

Table 2. Contributions of selected variables to the variation in % insufficient sleep in 2016 across counties in the contiguous United States

Variable	Slope Estimate	Standard Error	F Value	Pr > F	Partial R2 (%)	Model R2 (%)
Average Daily PM2.5	0.68	0.04	273.88	<.0001	29.04	29.04
Average Daily Max Air Temperature (F)	0.07	0.0a1	25.03	<.0001	4.49	33.53
Average Daily Precipitation (mm)	1.25	0.09	207.78	<.0001	4.16	37.69
Average Daily Sunlight (KJ/m^2)	0.0002	0.0001	8.00	0.0047	0.16	37.85

Note: Partial R^2 measures the marginal contribution of a given independent variable when another variable or variables are already included in the model. Model R^2 is a measure of the cumulative partial R^2 values, increasing with each additional variable added to the model.

Multiple regression models are estimated to measure the association between % insufficient sleep and each of the causes of death, adjusting for the environmental variables, in Table 3. There is a positive association between % insufficient sleep and each of the causes of death, except for Alzheimer's. In addition, % smokers, % adults with obesity, and % physically inactive are each positively associated with each of the causes of death. There is a negative association between Food Environment Index and each of the causes of death. A comparison of the F values indicates that death from all causes is most strongly associating with smoking, followed by sleep, physical inactivity, obesity, and finally diet. Specifically, of the five health behavior variables, % insufficient sleep has the 2nd strongest association with death from all causes. Its contribution is 3rd for heart disease, 3rd for tobacco-related cancers, 3rd for non-tobacco-related cancers, 5th for cerebrovascular disease, 3rd for diabetes, 5th for pneumonia/influenza, 5th for Alzheimer's, 5th for injury, and 5th for motor vehicle. Percent adult smokers had the strongest association with the causes of death, except for cerebrovascular disease where it was second to diet and for Alzheimer's where it was second to % adult obesity.

Table 3 Estimates of the association between the cause-specific mortality rates and % insufficient sleep and other health behaviors for counties in the contiguous United States, adjusting for weighted altitude and average daily sunlight, maximum air temperature, PM2.5, and precipitation

Age-adjusted Mortality Rates		% Insufficient Sleep	% Smokers	% Adults with Obesity	Food Environment Index	% Physically Inactive
All Causes	Slope Est	15.70	25.45	9.62	-42.92	10.30
	Std Error	0.63	0.58	0.42	2.10	0.42
	F Value	616.04	1951.19	513.09	416.57	591.41
	Pr > F	<.0001	<.0001	<.0001	<.0001	<.0001
Heart Disease (Aged 40+)	Slope Est	9.06	14.14	5.87	-27.62	7.45
	Std Error	0.50	0.49	0.33	1.63	0.32
	F Value	334.22	822.37	317.14	285.78	535.84
	Pr > F	<.0001	<.0001	<.0001	<.0001	<.0001
Tobacco-Related Cancer (Aged 40+)	Slope Est	3.20	5.67	1.94	-9.49	2.50
	Std Error	0.19	0.18	0.13	0.64	0.12
	F Value	295.35	944.17	239.19	219.59	416.23
	Pr > F	<.0001	<.0001	<.0001	<.0001	<.0001
Non-Tobacco-Related Cancer (Aged 40+)	Slope Est	1.97	3.06	1.12	-7.71	1.10
	Std Error	0.17	0.18	0.11	0.56	0.11
	F Value	140.61	303.91	100.06	192.89	96.26
	Pr > F	<.0001	<.0001	<.0001	<.0001	<.0001
Cerebrovascular Disease (Aged 40+)	Slope Est	0.99	1.79	0.83	-5.91	0.86
	Std Error	0.13	0.14	0.08	0.45	0.08
	F Value	62.47	168.64	98.26	173.20	105.90
	Pr > F	<.0001	<.0001	<.0001	<.0001	<.0001
Diabetes (Aged 40+)	Slope Est	2.34	3.94	1.57	-11.57	1.32
	Std Error	0.14	0.15	0.10	0.51	0.10
	F Value	263.25	721.34	257.25	506.69	173.28
	Pr > F	<.0001	<.0001	<.0001	<.0001	<.0001
Pneumonia/ Influenza (Aged 40+)	Slope Est	0.73	1.74	0.59	-2.90	0.81
	Std Error	0.10	0.10	0.07	0.37	0.06
	F Value	57.41	287.97	82.53	61.63	159.65
	Pr > F	<.0001	<.0001	<.0001	<.0001	<.0001
Alzheimer's (Aged 40+)	Slope Est	-0.29	0.55	0.36	-1.45	0.27
	Std Error	0.18	0.20	0.12	0.66	0.12
	F Value	2.89	7.43	9.14	4.79	5.35
	Pr > F	0.0903	0.0065	0.0025	0.0286	0.0208
Injury	Slope Est	1.43	3.43	1.12	-7.82	1.58
	Std Error	0.13	0.12	0.08	0.42	0.08
	F Value	125.11	760.38	173.97	345.46	363.70
	Pr > F	<.0001	<.0001	<.0001	<.0001	<.0001
Motor Vehicle	Slope Est	0.29	1.08	0.54	-2.71	0.67
	Std Error	0.05	0.05	0.03	0.17	0.03
	F Value	38.35	541.74	314.40	263.74	516.37
	Pr > F	<.0001	<.0001	<.0001	<.0001	<.0001

Tobacco-related cancers consist of oral cavity and pharynx, esophagus, stomach, pancreas, respiratory system, cervix uteri, urinary bladder, and kidney and renal pelvis.

Finally, % insufficient sleep is associated with each of the other health behaviors. When these variables were added with the environmental variables to the models, % insufficient sleep was no longer significantly associated with the cause-specific mortality rates, except for injury and motor vehicle, where significant positive associations continued.

Discussion

This study showed the prevalence of insufficient sleep in the contiguous US and the association it has with selected natural environmental factors health behaviors, and causes of death. The strength of the association between insufficient sleep and the causes of death was compared among the other health behaviors after adjusting for the environmental factors.

As altitude increases, the % insufficient sleep decreases. This association is explained by average daily sunlight, maximum air temperature, PM2.5, and precipitation, which correlate with altitude. Percent insufficient sleep was most strongly associated with average daily PM2.5, followed by maximum air temperature, precipitation, and then sunlight. The simultaneous significant association between these environmental factors and % insufficient sleep is consistent with the literature. Specifically, air pollution can hinder sleep through airway inflammation or autonomic nervous system pathway alterations [28]. Individuals exposed to higher levels of annual NO2 and PM2.5 are at greater risk for sleep apnea [28]. In a cohort study of Freshmen at a University in Beijing, China, air pollution correlated with reduced sleep duration [29]. In another cohort study, long-term exposure to PM2.5, PM10, and NO2 correlated with poor sleep quality in a cohort study conducted in rural China [30].

Air temperature is an important indicator of sleep quality [31]. Increases in nighttime temperatures in the summer months correlate with self-reported insufficient sleep [32]. Research concludes that the ideal temperature for sleeping is between 60 and 67 degrees Fahrenheit, with temperatures below 54 degrees and above 75 degrees as disruptive to sleep [33, 34]. Further, cooler body temperature correlates with deeper sleep [35].

Heavy precipitation may contaminate water quality (i.e., runoffs that may include heavy metals, pesticides, nitrogen, and phosphorus) [36]. Consequently, poor water quality may have a deleterious effect on sleep quality [37]. It is also possible that higher precipitation corresponds with higher levels of smoking, physical inactivity, and obesity, which, in turn, influence poorer sleep quality. In the model where % insufficient sleep was regressed on the environmental variables, the F value for precipitation was 207.78. After adding the health behavior variables, the F value for precipitation was 43.18.

Although the amount of variation in % insufficient sleep explained by average daily sunlight is small, after accounting for average daily PM2.5, maximum air temperature, and precipitation (Table 2), it had a positive association. It may be that counties with higher average daily sunlight, especially in the summer months, interfere more with a dark place for sleeping. At night, a darker sleep environment triggers the brain to make the hormone melatonin, which promotes sleep [38].

The positive association between % insufficient sleep and cause-specific mortality rates is consistent with the literature [1-16]. In the models adjusted for the environmental factors, % insufficient sleep continues to have a significant positive association with the cause-specific death rates, except for Alzheimer's.

Percent insufficient sleep continued to be significantly associated with the selected cause-specific mortality rates after adjusting for the natural environmental factors, except for Alzheimer's. The additional adjustment for the other health behaviors caused the associations to become insignificant, with the exceptions of injury and motor vehicle mortality. The persistent positive association between % insufficient sleep and deaths from injury and motor vehicles is consistent with other studies [15, 16]. The association observed in this study between % insufficient sleep and % smokers, % physically inactive, % obese, and poor diet is consistent with studies showing that these variables adversely affect sleep [39-42].

A few study limitations exist in this study. First, the ecologic study design means that measurements were on the county and not the individual level. Hence, ecologic fallacy may influence the results. However, the county level measurements for the natural environmental variables are appropriate since the people in the counties are similarly exposed. Although average daily maximum air temperature had a strong influence on the sleep variable, the full impact of temperature is unknown because people access climate-controlled homes, cars, and workplaces at different levels. The results were generally statistically significant because of the large number of counties involved. It is possible that some of the significant results may not be of practical importance. From a clinical perspective, it may be more informative to know about the modifiable health behaviors versus the less modifiable environmental factors. Finally, the cross-sectional, ecologic data limits our drawing strong conclusions about causal-effect relationships.

Conclusion

Counties with higher altitude experience better sleep duration, but this improvement is primarily explained by less fine particulate matter, more moderate ambient air temperature, and less precipitation at higher altitude. Improved sleep duration can occur with less pollution, moderate sleeping temperatures, and less precipitation. This finding involving precipitation may be because of water contamination associated with heavy precipitation and a correlation between greater precipitation and poorer health behaviors. After accounting for the environmental variables, insufficient sleep continues to have a direct adverse effect on the cause-specific mortality rates. Sleep duration may improve further by lower prevalence of tobacco smoking, obesity, physical inactivity, and poor diet. Finally, after accounting for the environmental and health behavior variables, insufficient sleep only continued to negatively impact death rates from injury and motor vehicle accidents. Because of the health implications association with insufficient sleep, consideration of the findings in this study may help direct health policy recommendations and influence individual behavior change.

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