

**QUANTITATIVE APPROACHES TOWARDS EVALUATING THE GLOBAL
BURDEN OF MENTAL ILLNESS**

by

Daniel Arias

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Abstract

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Table of Contents

Abstract	iii
Table of Contents	vi
List of Figures	vii
List of Tables	viii
Acknowledgements	ix
Introduction	1
1 Quantifying the global burden of mental disorders and their economic value	2
1.1 Introduction	3
1.2 Methods	6
1.2.1 Burden of mental disorders	6
1.2.2 Economic burden of disease	9
1.2.3 Sensitivity analyses	10
1.2.4 Statistical analysis	11
1.2.5 Ethics statement	11
1.2.6 Role of funding source	11
1.3 Results	13
1.4 Discussion	16
1.5 Acknowledgements	21
1.5.1 Author contributions	21
1.5.2 Declaration of interests	22
1.5.3 Data sharing statement	22
2 Climate exposures and population mental health in Madagascar: an ecological study of national health information system data	23
2.1 Introduction	24
2.2 Methods	25
2.2.1 Data	25
2.2.2 Statistical analysis	30
2.3 Results	35
2.3.1 Main analysis	41
2.3.2 Subgroup analysis	44
2.3.3 Multiverse analysis	46
2.4 Discussion	51
2.5 Acknowledgements	55
2.5.1 Author contributions	55
2.5.2 Funding statement	55
2.5.3 Declaration of interests	56
2.5.4 Data sharing statement	56

3 The impact of COVID-19 vaccine developments on Google COVID-19 search trends for mental health symptoms: a controlled interrupted time series analysis	57
3.1 Introduction	59
3.2 Methods	60
3.2.1 Data	60
3.2.2 Statistical analysis	62
3.2.3 Ethics statement	66
3.3 Results	66
3.4 Discussion	79
Conclusion	80
References	81
Supplementary materials	91
Appendix 1	91
Appendix 2	104
Appendix 2.1	104
Appendix 2.2	113

List of Figures

1	DALYs attributable to mental disorders in 2019, by estimation approach, as a share of all DALYs.	15
2	DALYs, YLDs, YLLs, and deaths attributable to mental disorders in 2019, by estimation approach, per 100,000 population.	17
3	Economic burden of mental disorders, as a percent of GDP.	18
4	Predominant ecoregions of Madagascar, summarized by administrative region.	32
5	Map of facilities in Madagascar, by GPS coordinate source and facility type.	36
6	Spatial distribution of climate conditions across clinics and seasons in Madagascar. .	37
7	Distribution of temperature and soil moisture across all month-years and all clinics. .	38
8	Tropical storms and cyclones in Madagascar by intensity and season, 2009-2010 to 2020-2021, inclusive.	39
9	Predicted values of monthly case counts and marginal effect estimates by coefficient and their 95% and 99% confidence intervals.	42
10	Effect estimates by coefficient with lagged exposures and their 99% and 95% confidence intervals, Model 4.	43
11	Specification curve depicting the effect estimates and confidence intervals for mean monthly temperature (degrees Celsius) across 192 models.	48
12	Specification curve depicting the effect estimates and confidence intervals for mean monthly soil moisture (percent saturation) across 192 models.	49
13	Specification curve depicting the effect estimates and confidence intervals for duration of cyclone activity across 192 models.	50
14	Interrupted time series (ITS) effect estimates and confidence intervals by symptom. .	67
15	Controlled interrupted time series effect estimates on Google Search density by symptom.	69
16	Density of Google Search trends for anxiety, by region, as a function of time.	70
17	Density of Google Search trends for depression, by region, as a function of time. .	71
18	Density of Google Search trends for major depressive disorder (MDD), by region, as a function of time.	72
19	CITS effect estimates and confidence intervals by mental health symptom, all model combinations.	73
20	Specification curve depicting the CITS effect estimates and confidence intervals for search density	75
21	CITS effect estimates and confidence intervals by mental health symptom, all model combinations.	76
22	CITS effect estimates and confidence intervals symptom, region, and predominant political ideology.	78
23	Communes and fokontany in Madagascar, by area.	129

List of Tables

Table 1.1: Comparison of the composition of the global burden of mental disorders, by estimation approach	7
Table 1.2: Disability-adjusted life years (DALYs) attributable to mental disorders as totals (millions) and percentages of overall burden, by estimation approach	12
Table 1.3: Global economic value associated with premature mortality and morbidity from mental disorders, by estimation approach and value per DALY.	14
Table 2.1: Alternative specifications, data processing, and modeling decisions for multiverse analysis	33
Table 2.2: Main analysis results, summarized by incidence rate ratios (IRRs) and average marginal effects (AME) from Models 1 through 4.	40
Table 2.3: Subgroup analysis results, summarized by incidence rate ratios (IRRs) and average marginal effects (AME) from Models 1 through 4.	46
Table 3.1: Alternative specifications, data processing, and modeling decisions for multiverse analysis	64
Table S1.1: The global economic burden of mental disorders, by year and approach, calculated by Bloom and colleagues and adjusted to 2019 USD using gross domestic product deflator adjustment. Estimates are in trillions.	91
Table S1.2: The economic value of mental disorder losses, using VSL approach, by year and monetary value assigned to one DALY. Authors' calculations based on Bloom and colleagues and adjusted to 2019 USD using gross domestic product deflator adjustment. Estimates are in trillions.	92
Table S1.3: Hierarchical classification of mental disorders in the Global Burden of Disease (GBD) 2019 study.	93
Table S1.4: Years lived with disability (YLDs) attributable to mental disorders as totals (millions) and percentages of overall burden, by World Bank income group classification and GBD region, under three estimation approaches.	94
Table S1.5: Years of life lost (YLLs) attributable to mental disorders as totals (millions) and percentages of overall burden, by World Bank income group classification and GBD region, under three estimation approaches.	95
Table S1.6: Deaths attributable to mental disorders as totals (millions) and percentages of overall burden, by World Bank income classification and GBD region, under three estimation approaches.	96
Table S1.7: The global economic burden associated with premature mortality and morbidity from mental disorders, by estimation approach and value per DALY, using alternative valuations.	97
Table S1.8: The economic burden associated with premature mortality and morbidity from mental disorders, by estimation approach and value per DALY, using alternative valuations and by World Bank income classification and GBD region.	98
Table S2.1: Availability of disaggregated health system data by year and level of care. . . .	104
Table S2.2: Mental health disorders reported in GESIS, in French and English.	105
Table S2.3: Yearly cumulative cases of mental and neurological disorders reported at primary facilities.	108
Table S2.4: Yearly cumulative cases of mental and neurological disorders reported at district hospitals.	108
Table S2.5: Yearly cumulative cases of mental and neurological disorders reported at regional hospitals.	109

Table S2.6: Standardization of region names.	115
Table S2.7: Standardization of district names.	115
Table S2.8: Standardization of district names, based on commune name.	116
Table S2.9: Standardization of commune names.	117
Table S2.10: Sample of facilities for validation.	131
Table S2.11: Distance between geolocated and validated coordinates.	131

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* * *

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To the steps we have taken already, and to the many we have ahead.

* * *

Introduction

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1 Quantifying the global burden of mental disorders and their economic value

Daniel Arias, Shekhar Saxena, Stéphane Verguet

A version of this paper was accepted for publication by *eClinicalMedicine* on September 9, 2022 and was published in Volume 54, Issue 101675 in December 2022.

Background: Epidemiological and economic estimates suggest that the global burden of mental disorders is considerable, both in its impacts on human health and losses to societal welfare. The availability of additional data and the emergence of new approaches present an opportunity to examine these estimates, which form a critical part in making the investment case for mental health.

Methods: This study reviews, develops, and incorporates new estimates and methods in quantifying the global burden of mental illness. Using a composite estimation approach that accounts for premature mortality due to mental disorders and additional sources of morbidity and applying a value of a statistical life approach to economic valuation, we determine global and regional estimates of the economic cost that can be associated with mental disorders, building on data from the 2019 Global Burden of Disease study.

Findings and interpretation: We estimate that 418 million disability-adjusted life years (DALYs) could be attributable to mental disorders in 2019 (16% of global DALYs), a more than three-fold increase compared to conventional estimates. The economic value associated with this burden is estimated at about USD 4.7 trillion. At a regional level, the losses account for between 3.9% of gross domestic product in Eastern Sub-Saharan Africa and 7.9% in High-income North America. Taken together, our findings suggest that the burden of mental illness in terms of both health and economic losses may be much higher than previously assessed.

Keywords: mental health, disease burden, premature mortality, economic burden.

1.1 Introduction

Mental health is an essential part of human flourishing. As defined by the World Health Organization (WHO), it encompasses “a state of well-being in which every individual realizes [their] own potential, can cope with the normal stresses of life, can work productively and fruitfully, and is able to make a contribution to [their] community.²” For much of the global population, however, attaining this state of mental health is an enduring challenge, with over one billion people worldwide living with a mental or addictive disorder.³ Mental disorders are both leading causes of disability and significant risk factors for premature mortality.^{3,4} At all levels of sociodemographic development, this burden of morbidity and mortality is rising.⁵ Furthermore, as the COVID-19 pandemic continues, there is growing and alarming evidence of its detrimental psychological and psychiatric effects—for patients, health care workers, and the public overall.⁶

The magnitude of disability caused by mental disorders has galvanized a global movement and a call to action for greater investment and prioritization for mental health.⁷ This movement has emphasized the importance of investing in mental health as a means of promoting sustainable development, human rights, and social inclusion.⁵

A critical link between mental health and development arises from the economic consequences of mental disorders. A growing body of literature suggests that mental disorders are costly, both in the direct medical costs of care, outpatient visits, and hospitalizations, and in indirect costs, such as losses in income and productivity due to disability, which may cause absenteeism and presenteeism.⁸ These costs further worsen conditions of poverty⁹—a vulnerability that, in turn, worsens mental health, feeding a vicious cycle of poverty and illness.¹⁰ At the national level, mental disorders deplete the supply of labor and capital, resulting in poorer economic output.¹¹ Among households and nations alike, the burden of mental illness thus has considerable economic consequences and poses a challenge to both health and wealth.

Evaluating the economic burden of mental illness is a critical part in making the investment case for global mental health, informing public health decision-making, and guiding priority-setting and the scale up of much-needed interventions.¹² At the global level, however, the most recent estimate of the economic impact of mental disorders was published in 2011, using burden of disease estimates from 2004.¹³ This study used three distinct approaches to quantify the economic burden of non-communicable diseases (NCDs), including mental illnesses.¹³ The first is a cost-of-illness (COI) analysis, which includes the direct costs of illness as well as the indirect costs (e.g., lost productivity). The second is a value of lost output approach, which estimates the effects of illness on gross domestic product (GDP) due to the depletion of labor and capital. The third builds from value of a statistical life (VSL) approaches and attempts to capture a population's willingness to pay to reduce morbidity and mortality associated with illness. This expands on the COI and value of lost output approaches, as it puts an economic value on the loss of health itself.

With a third of disability-adjusted life years (DALYs) due to NCDs arising from mental disorders, this landmark paper estimated that the value of losses due to mental disorders was roughly 1.3 trillion USD in 2010 (1.6 trillion USD in 2019) when DALYs were valued at one times GDP per capita.¹³ The authors further projected that these losses would grow to nearly 2.5 trillion USD 2010 (or approximately 3.0 trillion USD in 2019) by 2030. (See Tables S1.1 and S1.2 in Appendix 1 for estimates from the other two approaches.) These estimates have been widely cited in calls to action concerning global mental health.^{5,14}

While the estimates presented from this paper remain staggering and salient, new studies estimating the morbidity and mortality associated with mental illness have since become available.^{15–17} These studies suggest that previous (and current) estimates of the global burden of mental disorders may be considerably underestimated, which, in turn, has implications for estimating the true economic burden of mental illness.

The most recent estimates of morbidity and mortality due to mental disorders come from the Global Burden of Disease (GBD) 2019 study.¹⁸ The GBD study provides disease burden estimates using DALYs, years of life lost (YLLs), and years lived with disability (YLDs), which are then aggregated within a hierarchical grouping scheme that classifies causes of disability and death at different levels of mutually exclusive and completely exhaustive categories. (Mental disorders are a Level 2 condition, nested under NCDs; see Table S1.3.)

While GBD remains the gold standard for global epidemiologic estimation, the nature of the GBD scheme—in particular, the rationale for grouping certain conditions under mental disorders or not—has been the subject of debate in the literature.^{16,19,20} In particular, work by Vigo et al. (2016) published in *The Lancet Psychiatry* argues for an expanded classification of mental disorders under the GBD classification scheme to account for underestimation of the burden of mental disorders.¹⁶ The authors attribute this underestimation to five main causes: 1) the distinction drawn between mental and neurological diseases; 2) the categorization of self-harm and suicide under injuries; 3) the classification of all chronic pain and somatoform disorders under musculoskeletal disorders; 4) the exclusion of personality disorders; and 5) the exclusion of premature mortality due to mental disorders. Using data from the 2013 GBD study, Vigo and colleagues re-allocated the entire burden of dementias, epilepsy, migraine, tension-type headache, and self-harm to mental disorders. In addition, a third of the burden of musculoskeletal disorders without anatomical correlate (i.e., somatoform disorders with prominent pain) was attributed to mental disorders.¹⁶ This reallocation attributed 13% of DALYs to mental disorders, a 6 percentage point increase from the GBD estimate of 7%.

In this paper, we attempt to revisit the estimation of the global burden of mental disorders and of its associated economic value. Our aim is to characterize potential underestimation of the burden of mental disorders and to quantify the economic value of this burden under different estimation

approaches. Specifically, we expand on Vigo et al.¹⁶ by capturing premature mortality due to mental disorders using pooled risk ratios of mortality from a systematic review of mental disorders¹⁷ to determine the population attributable fraction (PAF) of premature mortality. Inclusion of premature mortality through the PAF presents a novel composite approach that can more broadly capture attributable morbidity and mortality. Using this approach on GBD 2019 estimates, we then apply monetary values to DALYs to reach estimates of the global economic value of the mental burden of disease using a VSL approach. The VSL approach—in contrast to COI and VLO approaches—includes an economic valuation of mortality risk reductions in monetary terms, and thus enables comparison across sectors (beyond the sole health sector) which can motivate decision-making toward ameliorating welfare and societal mental health. Our findings suggest that both the epidemiological and economic burden of mental disorders could be larger than previously estimated, and that underestimation would be larger among regions where premature mortality due to mental disorders is greater.

1.2 Methods

To estimate the economic burden of mental disorders, we first estimate the attributable mental burden of DALYs under various estimation approaches using data from the 2019 GBD study (available from the Global Health Data Exchange at <https://ghdx.healthdata.org/gbd-2019>). Second, we apply a monetary value to a DALY to yield an economic assessment associated with these burden estimates.

1.2.1 Burden of mental disorders

In our analysis, we replicate the approach of Vigo et al. (2016) using GBD 2019 estimates, applying a similar re-allocation formula to YLLs, YLDs, DALYs, and deaths. Our approach, however, differs

in some key respects.

First, we agree with Whiteford and colleagues in viewing the assigning of the entire burden of suicide and self-harm to mental disorders as an overestimate, and consequently do not reallocate all DALYs due to suicide towards the mental health burden.²⁰ While it is empirically clear that mental disorders elevate the risk of death by suicide and that the majority of suicides appear to be due to mental disorders,²¹ we view assigning the entirety of this burden to mental disorders as overinclusive, which we avoid to favor a conservative estimation strategy.

Second, we attempt to capture premature mortality attributable to mental disorders, recognizing that persons with mental disorders are at elevated risk of all-cause mortality,¹⁷ unnatural death,²² and deaths due to natural causes.²³ Not capturing this share of mortality is likely to be a prominent cause of underestimating the burden of mental illness, particularly in countries where the dominant share of the DALY burden is mortality (rather than morbidity).

Following Vigo and colleagues, we replicate reallocations in neurological and musculoskeletal conditions, and further include alcohol and mental use disorders, as these were previously classified under mental disorders within the GBD classification.

This provides estimates of YLDs due to mental disorders. We then estimate the PAF of mortality due to mental disorders, using GBD prevalence estimates and relative risk estimates for natural-cause and unnatural-cause mortality generated from a systematic review and meta-analysis by Walker et al.¹⁷ A comparison of our allocation approach with those of Vigo et al. and the original GBD hierarchical allocation is shown in Table 1.1.

Table 1.1: Comparison of the composite allocation approach with the reallocation approach and with the original Global Burden of Disease (GBD) hierarchical allocation, with respect to the burden of mental disorders

	Original allocation	2. Reallocation approach (Vigo et al. 2016)	3. Composite approach
<i>Schizophrenia</i>	Yes	Yes	Yes
<i>Depressive, bipolar, anxiety disorders</i>	Yes	Yes	Yes
<i>Eating disorders</i>	Yes	Yes	Yes
<i>Autism spectrum, AD(H), and conduct, disorders</i>	Yes	Yes	Yes
<i>Substance abuse disorders</i>	Included in GBD 2016; classified separately since GBD 2017	Yes (with additional deaths due to alcohol use included in Vigo et al. 2020)	Yes
<i>Neurological disorders</i>	No	Yes	Yes
<i>Chronic pain syndrome and somatoform pain disorders</i>	No	Yes, 33% of DALYs	Yes, 33%
<i>Self-harm / suicide</i>	No	Yes, all DALYs	Yes, % of YLLs due to unnatural death based on PAF
<i>Premature mortality due to mental disorders</i>	No	No	Non-communicable diseases: Yes, % of YLLs due to natural death based on PAF Infectious, maternal, and neonatal diseases: No

Our approach to capturing premature mortality relies on a pooled relative risk estimate for mortality by natural and unnatural causes, drawn from 148 studies identified by Walker et al.¹⁷ These studies collectively reflect over 338,000 deaths across 29 countries and 6 continents. The

majority of deaths (67%) recorded in studies with disaggregated data arose from acute and chronic illnesses, while unnatural causes such as injury and suicide represented 18% of deaths (the rest being unallocated). Overall, the pooled risk of all-cause mortality was 2.2 times higher (95% confidence interval (CI): 2.1-2.3) among people with mental disorders compared to those without. Using this relative risk estimate, Walker and colleagues calculated a PAF to estimate that 8 million deaths were due to mental disorders in 2012.

While Walker and colleagues used a global estimate of the worldwide prevalence of mental disorders in their study to calculate the PAF, we use GBD estimates of prevalence to derive both global- and country-level results. The PAF for a given disorder d and country c is given by:

$$PAF_{(d,c)} = \frac{p_{(d,c)} (RR_d - 1)}{1 + p_{(d,c)} (RR_d - 1)} , \quad (1.1)$$

where $p_{d,c}$ is the prevalence of a given disorder in a country and RR_d is the relative risk of mortality estimated by Walker et al.¹⁷

We separately estimate the PAF for natural and unnatural causes of mortality. Using the calculated PAF estimates, we estimate YLLs attributable to mental disorders by multiplying the PAF by the national burden of mortality. For natural causes of death, we conservatively apply the PAF against YLLs attributable to NCDs. For unnatural causes of death, we apply the PAF against YLLs due to self-harm and injuries. These YLLs are then combined with the YLDs calculated previously to provide DALYs.

1.2.2 Economic burden of disease

To estimate the economic cost associated with premature mortality and morbidity tied to mental illnesses, we assigned a monetary value to attributable DALYs. VSL approaches assign a monetary value to small reductions in mortality risks.²⁴ Drawing from these approaches, Jamison and colleagues

have estimated monetary values of statistical life years,²⁵ which Khadka and colleagues recently adapted to quantify the economic value of changing mortality risk by cause of death in low- and middle-income countries (LMICs).²⁶ While VSL approaches are not meant to assign monetary values to full life years or years lived with illness or disability,²⁴ the Copenhagen Consensus has previously implemented the use of GDP per capita as a proxy for the monetary value of a DALY as a standard estimate.²⁷ Values of one and three times GDP per capita have been suggested as proxies for the value of a DALY.^{28,29} Estimates of \$1,000 and \$5,000 per DALY have been used, with the justification that these would be reasonable and convenient lower and upper values, particularly for low-income and lower-middle income countries.^{30,31}

Consistent with previous approaches, we use GDP per capita (USD 2019) for our base-case value of a DALY. GDP inputs are reported in 2019 USD and obtained from the World Bank's World Development Indicators; for consistency with our epidemiological inputs, we convert to per capita values using GBD population estimates.

1.2.3 Sensitivity analyses

The primary focus of this paper concerns structural uncertainty in determining the burden of mental illness, resulting in the evaluation of three different estimation approaches. To address parameter uncertainty within each approach, we apply a three-way sensitivity analysis. First, following a simple intuitive approach, we incorporate the upper and lower uncertainty intervals (UIs) provided by GBD 2019 for YLLs, YLDs, and DALYs to account for parameter uncertainty. Second, we use the upper and lower values of prevalence estimates and of the 95% confidence intervals (CIs) of the pooled relative risk of all-cause mortality from Walker and colleagues in our composite approach.¹⁷ Third, our lower bound estimates are set to reallocate one sixth of the burden of musculoskeletal disorders proposed by Vigo and colleagues,¹⁶ while our upper bound estimates are set to reallocate

one half of this burden.

In addition to our base-case economic valuation, we further report our VSL estimates using three times GDP per capita as the value of a DALY. (Alternative valuations using values of \$1,000 and \$5,000, as well as purchasing power parity (PPP)-adjusted GDP per capita, are reported in Tables S1.5 and S1.6 of Appendix 1)

1.2.4 Statistical analysis

All analyses were completed using R (version 4.2.1).³²

1.2.5 Ethics statement

The research draws exclusively on secondary country-level data reported at the national or subnational level. As such, it does not involve data collection, experimentation, or investigation concerning human subjects. The Institutional Review Board (IRB) of the Harvard T.H. Chan School of Public Health has determined that the study was not human subjects research, and that additional review was not required (protocol number: IRB20-1946, determined on November 13, 2020).

1.2.6 Role of funding source

This study received no funding. All authors (DA, SV, and SS) had access to the data and shared in the decision to submit this article for publication.

Table 1.2: Disability-adjusted life years (DALYs) attributable to mental disorders as totals (millions) and percentages of overall burden, by World Bank income group classification and GBD region, under three estimation approaches.

	Original approach						Reallocation approach						Composite approach					
	DALYs			% of burden			DALYs			% of burden			DALYs			% of burden		
	Estimate	Lower bound	Upper bound	Estimate	Lower bound	Upper bound	Estimate	Lower bound	Upper bound	Estimate	Lower bound	Upper bound	Estimate	Lower bound	Upper bound	Estimate	Lower bound	Upper bound
Global	125.3	93.0	163.2	4.9	4.1	5.8	321.2	198.6	505.2	12.7	8.7	18.0	417.7	276.7	608.4	16.5	12.1	21.6
High income	24.5	18.1	32.0	6.7	5.7	7.6	74.4	46.2	117.9	20.3	14.4	28.1	81.0	52.8	120.3	22.1	16.5	28.7
Upper-middle income	45.6	33.8	59.7	5.6	4.7	6.4	117.5	69.5	191.6	14.3	9.7	20.5	156.6	99.3	236.2	19.1	13.9	25.3
Lower-middle income	44.9	33.0	58.9	4.3	3.6	4.9	108.8	65.0	174.1	10.4	7.1	14.6	147.4	90.2	225.7	14.1	9.8	18.9
Low income	10.1	7.4	13.5	3.4	2.9	3.8	20.3	12.0	32.6	6.7	4.6	9.3	32.3	19.8	49.9	10.7	7.7	14.2
East Asia	21.0	15.7	27.3	5.3	4.5	6.0	55.8	32.8	91.8	14.1	9.5	20.3	72.7	45.6	109.7	18.3	13.2	24.3
Southeast Asia	9.1	6.7	11.9	4.6	3.9	5.3	23.3	12.4	40.4	11.8	7.2	17.8	32.3	18.8	52.0	16.3	11.0	22.9
Oceania	0.2	0.1	0.2	3.0	2.7	3.3	0.4	0.2	0.6	7.1	4.7	9.8	0.6	0.4	1.0	12.2	8.6	16.2
Central Asia	1.3	0.9	1.7	4.4	3.7	5.1	3.7	2.3	5.8	13.1	9.3	17.8	4.7	2.9	7.2	16.4	11.8	22.0
Eastern Europe	3.5	2.6	4.5	3.9	3.3	4.5	13.4	9.0	20.2	15.1	11.5	20.0	16.1	10.7	23.5	18.1	13.6	23.3
Central Europe	1.7	1.3	2.3	4.3	3.7	4.8	5.7	3.4	9.4	14.1	10.0	19.9	6.8	4.2	10.5	16.8	12.2	22.3
Caribbean	0.8	0.6	1.0	5.2	4.5	5.8	1.7	1.0	2.8	11.7	8.2	16.0	2.7	1.7	4.1	18.0	13.3	23.5
Central Latin America	4.1	3.0	5.5	6.2	5.3	7.0	10.1	5.9	16.4	15.1	10.4	21.0	14.2	8.9	21.8	21.3	15.5	27.9
Tropical Latin America	5.1	3.7	6.6	7.5	6.2	8.8	11.6	7.0	18.6	17.3	11.7	24.7	16.9	11.7	24.1	25.2	19.5	32.1
Andean Latin America	1.1	0.8	1.4	7.0	6.1	7.8	2.3	1.4	3.8	15.0	10.5	20.3	3.2	1.9	4.9	20.4	14.9	26.7
North Africa and Middle East	10.7	7.8	14.1	8.0	6.9	9.0	21.5	12.3	35.3	16.0	10.8	22.5	31.3	19.3	48.1	23.4	17.0	30.7
Southern Sub-Saharan Africa	1.2	0.9	1.6	3.2	2.6	3.8	3.2	2.0	4.9	8.3	5.7	11.6	4.7	3.1	6.8	12.3	9.0	16.1
Western Sub-Saharan Africa	6.7	4.9	9.0	2.6	2.2	2.9	14.7	8.2	24.5	5.6	3.6	8.0	20.8	11.9	33.5	7.9	5.3	10.9
Central Sub-Saharan Africa	2.1	1.5	2.8	3.7	3.1	4.2	4.1	2.4	6.6	7.2	4.9	9.9	6.4	3.8	9.9	11.0	7.7	14.8
Eastern Sub-Saharan Africa	5.8	4.2	7.7	3.5	2.9	4.0	11.3	6.9	17.8	6.8	4.8	9.2	15.8	9.9	24.2	9.5	6.8	12.6
South Asia	28.8	21.2	37.6	4.6	3.8	5.3	70.8	43.3	111.1	11.2	7.7	15.6	96.0	59.9	144.2	15.2	10.7	20.2
Southern Latin America	1.3	0.9	1.6	6.9	5.7	8.1	3.1	1.9	4.8	16.9	11.9	23.5	3.8	2.6	5.5	21.1	16.0	27.0
Western Europe	9.4	7.0	12.4	7.5	6.3	8.6	25.6	15.3	41.9	20.2	13.8	29.0	28.5	18.4	42.6	22.5	16.6	29.5
High-income North America	8.0	6.0	10.4	6.6	5.6	7.6	27.1	18.1	40.7	22.4	17.0	29.7	29.0	19.5	41.7	23.9	18.3	30.4
Australasia	0.7	0.5	0.9	9.5	8.1	10.8	1.7	1.1	2.6	22.9	17.0	30.5	1.9	1.3	2.7	25.2	19.7	31.4
High-income Asia Pacific	2.7	2.0	3.5	5.4	4.5	6.1	9.8	5.7	16.3	19.6	13.1	28.4	9.1	5.8	13.8	18.1	13.2	24.0

1.3 Results

Under GBD 2019, over 125 million DALYs were attributed to mental disorders, or roughly 5% of the global burden. After including alcohol and drug use, neurological disorders, chronic pain, suicide, and self-harm, the share due to mental disorders rose to 12% of global DALYs (approximately 321 million DALYs). Under the composite approach, an additional 97 million DALYs were attributed to mental disorders, encompassing, in total, over 16% of global DALYs (Figure 1). Under all three methods, the burden of mental disorders (in DALYs) exhibited a country-income gradient, with mental disorders comprising over twice the burden of disease in high-income countries compared to low-income countries.

Rates of DALYs and deaths attributable to mental disorders under the different estimation approaches are presented by GBD region (Figure 2). Geographically, the composite approach allocated a large portion of DALYs (to mental disorders) in Eastern Europe, North and Latin America, and sub-Saharan Africa. This is largely driven by the inclusion of premature mortality in the composite approach. Estimates of DALYs by country income group and GBD region are reported in Table 1.2. (Estimates of deaths are reported in Table S1.4-1.6.)

Under the three approaches, we calculated the economic value of mental disorder losses (Table 1.3). Using GDP per capita as a proxy for the value per DALY, economic losses due to mental disorders were estimated at 4.7 trillion USD using our composite approach. This estimate is 1.1 trillion USD larger than that reached using the 2016 reallocation approach and over 3.3 trillion USD larger than that reached from the unadjusted GBD 2019 estimates.. Further adjusting for purchasing power parity, the global value of mental illness losses would exceed 7.2 trillion international dollars in 2019 (Table S1.7).

Table 1.3: Global economic value associated with premature mortality and morbidity from mental disorders, by estimation approach and value per DALY. Estimates are in trillions 2019 USD. DALY: disability-adjusted life year. USD: United States dollar. GDP: gross domestic product.

Value per DALY (USD, 2019)	Original approach			Reallocation approach			Composite approach		
	Estimate	Lower bound	Upper bound	Estimate	Lower bound	Upper bound	Estimate	Lower bound	Upper bound
<i>1x GDP/capita</i>	1.42	1.06	1.85	3.64	2.25	5.73	4.74	3.14	6.90
<i>3x GDP/capita</i>	4.27	3.17	5.55	10.93	6.76	17.20	14.22	9.42	20.71

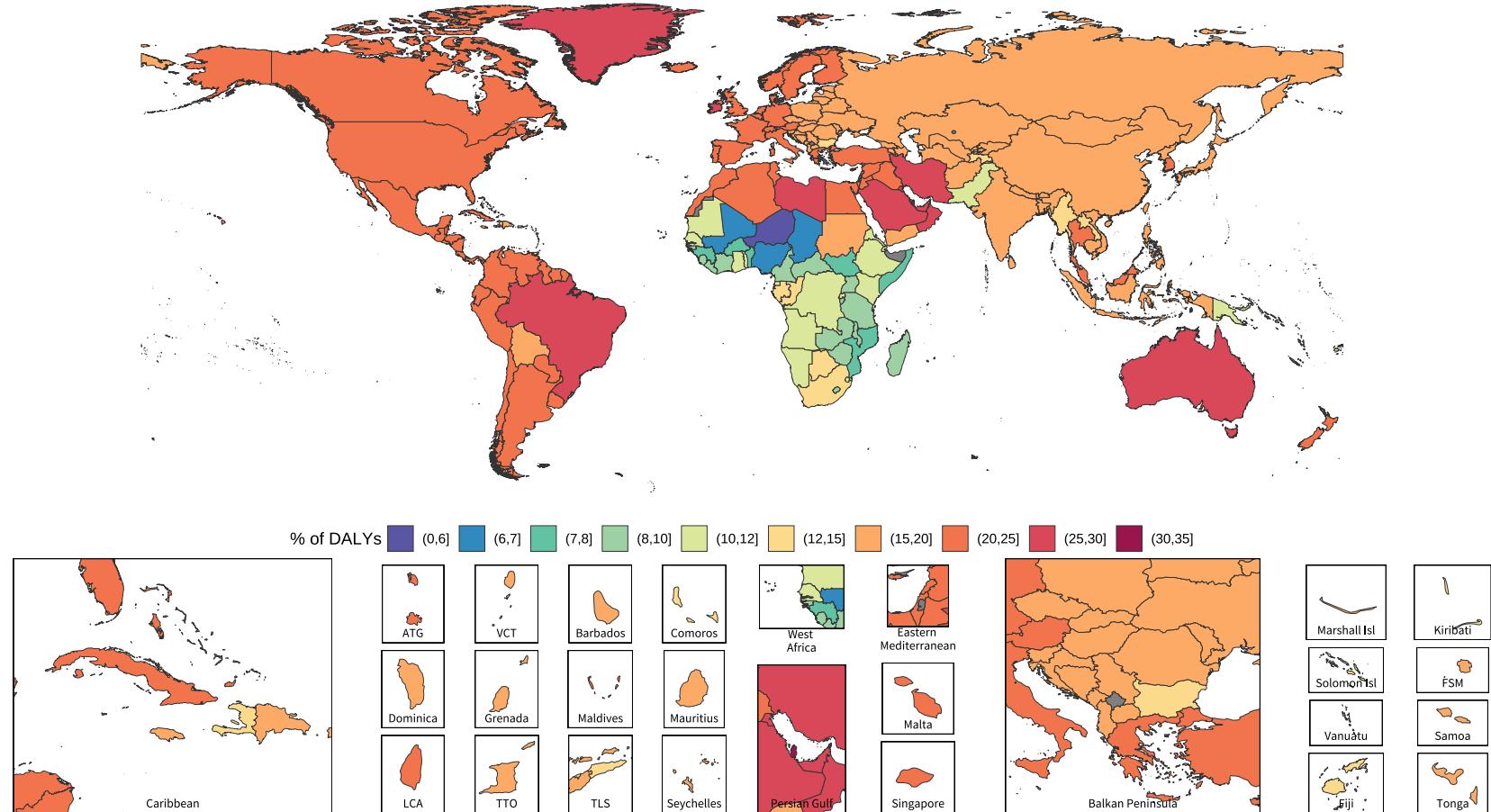


Figure 1: DALYs attributable to mental disorders in 2019, by estimation approach, as a share of all DALYs. ATG: Antigua and Barbuda; DALYs: disability-adjusted life years; FSM: Federated States of Micronesia; LCA: Saint Lucia; TLS: East Timor; TTO: Trinidad and Tobago; VCT: Saint Vincent and the Grenadines.

Although economic losses do not represent an actual loss to GDP, a sense of the scale can be gained by expressing the economic consequences with respect to GDP. Figure 3 displays the economic burden of disease due to mental disorders under the three estimation approaches by GBD region, as a percent of regional GDP. (Estimates by absolute values per DALY are provided in Appendix 1, along with mapped data visualizing estimates across all values per DALY.) Across approaches, the greatest change in estimated burden occurs in Eastern Europe, Latin America, North America, and Southern sub-Saharan Africa. Under the relative GDP-per-capita values the economic burden would account for between 3.9% of gross domestic product in Eastern Sub-Saharan Africa and 7.9% in High-income North America under our composite approach.

1.4 Discussion

This study explores possible alternative approaches to estimating the global burden of mental illness and the economic losses thereof. In particular, we propose a composite approach to address contention in the classification of mental disorders. This approach suggests that the global DALYs attributable to mental disorders could exceed 418 million per year, or 16% of the total burden.

When applied against an economic value per DALY of one times GDP per capita, this approach further suggests that the per year losses associated with this burden could exceed 4.7 trillion USD in 2019. When adjusting for the uncertainty in estimates of the attributable burden of disease, the losses could range from 3.1 trillion to more than 6.9 trillion USD. Adjusting for purchasing power parity would increase the magnitude of these estimates, with ranges from 4.8 to 10.6 trillion international dollars at the global scale.

Put in context of the existing literature, our epidemiological and economic estimates provide two important contributions. First, our findings echo in magnitude those of Vigo and colleagues,¹⁶ which have highlighted that suicide and premature mortality due to mental disorders are potentially

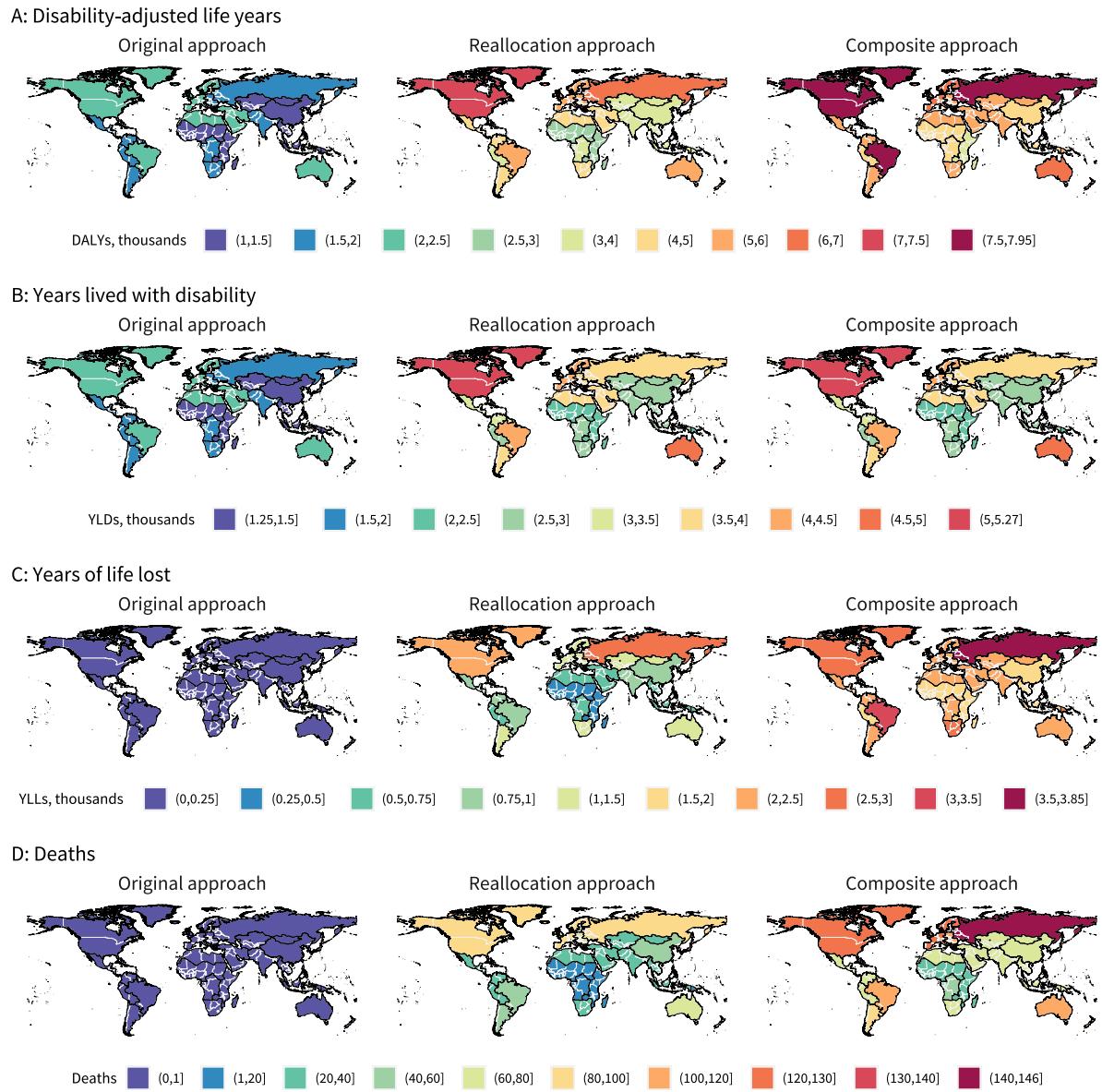


Figure 2: DALYs, YLDs, YLLs, and deaths attributable to mental disorders in 2019, by estimation approach, per 100,000 population. Values are aggregated by GBD region. DALYs: Disability-adjusted life years; YLDs: years lived with disability; YLLs: years of life lost; GBD: Global Burden of Disease.

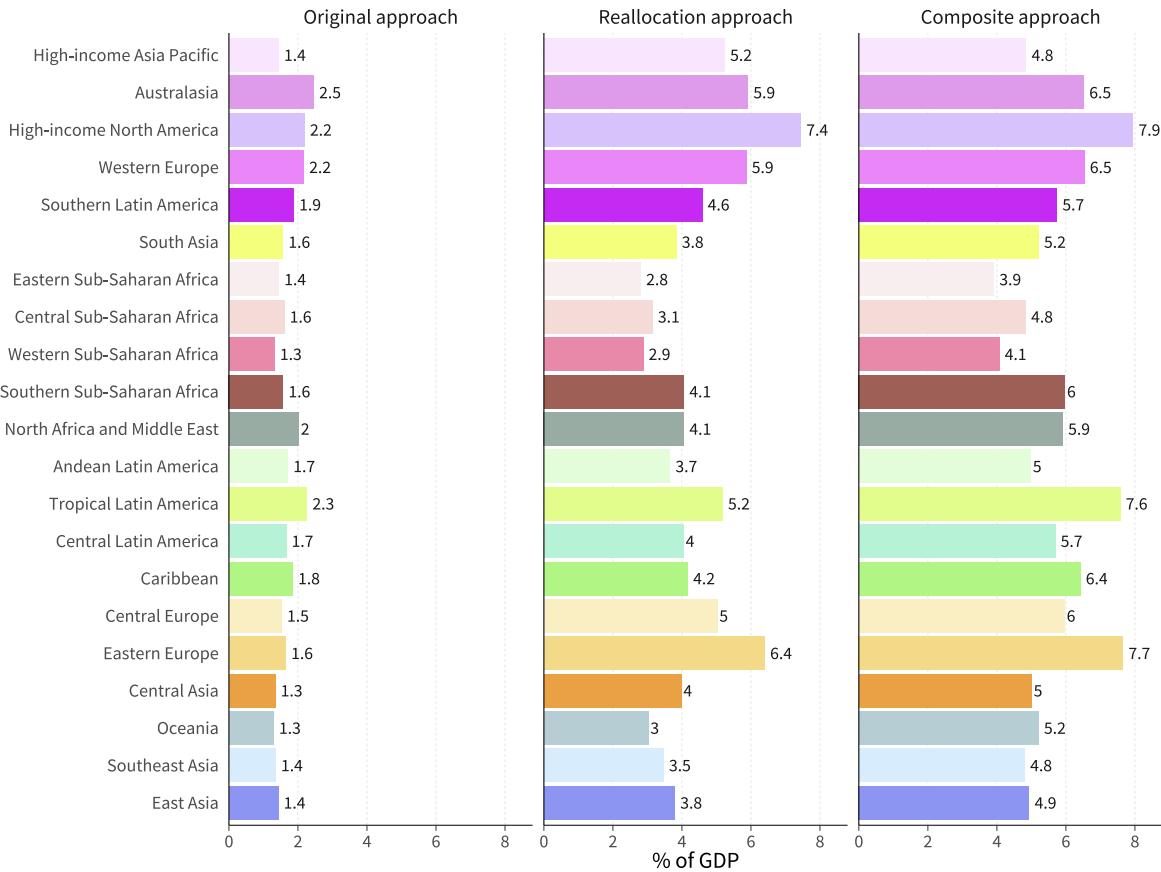


Figure 3: Economic burden of mental disorders, as a percent of GDP. The economic value is determined by using GDP per capita (USD 2019) as the value of a DALY. Values are aggregated by GBD region. GDP: gross domestic product; USD: United States dollar; DALY: disability-adjusted life year; GBD: Global Burden of Disease.

large sources of underestimation in the current GBD classification. Second, when including these sources of attributable mortality, the economic findings suggest staggering losses. We estimate that in 2019, the losses would already be over 1.8 trillion USD greater than Bloom and colleagues' global losses projections for 2030 (2.9 trillion 2019 USD, using the same value per DALY approach).¹³

Our findings add to a growing literature concerning the classification of mental disorders, in particular related to underscoring the importance of including premature mortality attributable to mental disorders in burden conceptualizations.^{16,20,33,34} These calls have most recently been emphasized by GBD collaborators who have urged that "the differential mortality gap for individuals with mental disorders needs to be reflected within the GBD framework."¹⁵ Our composite approach to assigning attributable mortality presents one potential attempt for acknowledging this differential mortality gap. Our economic analysis further provides updated monetary estimates of the burden of mental illness; to our knowledge, this is the first such analysis of the global economic burden of mental disorders in over a decade.

Our results should, however, be interpreted with several limitations in mind. First, our estimation approaches themselves all draw upon modeled data (i.e., GBD estimates). While GBD generates descriptions of morbidity and mortality at fine demographic and geographic levels, it is important to emphasize that the sophisticated modeling approaches implemented often draw on (potentially little) available underlying empirical data.³⁵ These inputs can be extremely limited for particular diseases and geographical locations, especially so for mental disorders. By way of example, the GBD 2019 Data Input Sources Tool retrieves 3,084 separate data sources for mental disorders. Of these, only 60 pertain to sub-Saharan Africa (1.9%) and 58 to South Asia (1.8%).³⁶ By comparison, of the 6,064 records pertaining to maternal and neonatal disorders, 631 are for sub-Saharan Africa (10.4%) and 270 for South Asia (4.5%). These severely limited inputs reflect a dearth of global mental health data; as of 2017, the World Mental Health survey initiative had conducted interviews

in just 26 countries, only 13 of which were classified as low- or middle-income.³⁷

Relatedly, our composite approach relies on pooled estimates of the relative risk of mortality from a systematic review and meta-analysis that itself is limited by the available data it draws upon.¹⁷ The review identified 203 studies for inclusion, of which only two were located in Africa, 16 in Asia, and one in South America. While the authors found that the estimates of mortality risk did not vary by region, the limited representation of studies from the world's most populous and epidemiologically diverse continents is a considerable shortcoming. It is possible, for instance, that the relative risk of all-cause mortality associated with mental disorders is lower where the burden of mortality is more heavily concentrated among child, maternal, and infectious diseases, and is higher where the burden is dominated by NCDs. Therefore, to reach a conservative estimate of attributable mortality, we separately estimated population attributable fractions for natural and unnatural causes of death and restricted our allocation of YLLs from natural causes to NCDs—meaning no deaths from maternal or infectious diseases were attributed to mental disorders under the composite approach.

Furthermore, our composite approach allocates mortality due to mental disorders by calculating population attributable fractions using the conventional formula, which may be biased in the presence of confounding or effect heterogeneity.³⁸ In particular, the use of adjusted risk ratios (as in the current analysis) may result in anticonservative bias if the crude risk ratios are lower than the adjusted ones. To mitigate the potential for bias, our sensitivity analysis presents results under conservative assumptions for risk ratios and estimates of prevalence and mortality.

Despite these limitations, our findings underscore both that the true burden of mental disorders may only partially be captured by current estimation approaches, and that, consequently, the associated economic losses may be much higher than previously estimated. We note that our findings may themselves be an underestimate, as our composite approach excludes deaths due to

neonatal, maternal, and infectious diseases attributable to mental disorders. However, we observe that conventional estimation approaches may fail to capture large shares of premature mortality attributable to mental health causes, both from self-inflicted and unnatural causes of death and mortality from NCDs. Capturing this share of the burden emphasizes that mental health is a critical risk factor for premature mortality, as well as a direct source of morbidity.

The magnitude of economic costs associated with mental disorders raises the need for health economics research, particularly on returns on investment and costing for effective prevention and treatment strategies.³⁹ Further work is also needed to strengthen the measurement of the global burden of mental illness, not only for more fully capturing the morbidity and mortality of mental disorders, but also for incorporating the impacts of new and evolving threats—such as pandemics, conflicts and climate change—to population mental health.

Our study highlights that mental health—far from being an issue solely concentrated in high-income regions alone—is a major global issue, one that imposes a significant toll to health and welfare. The large magnitude of these twin burdens highlights the urgency for global action to support mental health financing and to bolster its prioritization.

1.5 Acknowledgements

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1.5.1 Author contributions

All authors contributed to study conception, methodology, and interpretation. DA oversaw data acquisition, programming, formal analysis, visualization, the first draft of the manuscript. All

authors contributed to critical revision of the manuscript, with responses to reviewers and subsequent revisions led by DA. All authors had access to and verified all the data and accept responsibility for the decision to submit for publication.

1.5.2 Declaration of interests

We declare no competing interests.

1.5.3 Data sharing statement

GBD estimates are available for download from the Global Health Data Exchange and are available freely for non-commercial users under the Open Data Commons Attribution License (<https://ghdx.healthdata.org/gbd-2019>). All codes used for the analysis in this article are available on GitHub (https://github.com/darias5/gmh_econ).

2 Climate exposures and population mental health in Madagascar: an ecological study of national health information system data

Daniel Arias, Karestan Koenen, Christopher Golden

Background: Climate change-related exposures (CCEs) have been increasingly linked to worsened mental health, yet few studies of CCEs have taken place in low- and middle-income countries.

Methods: To better understand how climate conditions may be impacting population mental health in these settings, we leverage meteorologic, geospatial, and health system data reported by 3,378 facilities in Madagascar from 2010 to 2020 to explore the mental health impacts of three exposures of climate using negative binomial regression: temperature, soil moisture, and duration of cyclones and tropical storms.

Findings and interpretation: We found a statistically significant reduction in monthly cases associated with temperature—approximately 4.2% fewer cases reported per each degree Celsius (IRR: 0.958, $p = 0.038$, 99% CI: 0.909 – 1.01). A multiverse analysis of 192 models found this estimate to be robust to alternative specifications, while a subgroup analysis by ecoregion indicated that this association was primarily localized to facilities in the central highlands, where cooler temperatures are more prevalent. We further found that higher soil moisture may be associated with higher case counts in the future, with an 8.5% elevation in incident cases reported (IRR: 1.085, $p < 0.0001$, 99% CI: 1.046 – 1.127) after a lag of three months. We further found that greater soil moisture was associated with higher cases reported in the eastern lowlands and the northern dry deciduous forests, which is consistent with the geographic concentration of flood risk in Madagascar.

Keywords: *climate mental health, planetary health, eco-anxiety, climate change, humidity, soil moisture, drought, temperature, cyclones.*

2.1 Introduction

As empirical evidence increasingly highlights the wide-scale impact of human activities on climate, there is a growing, parallel body of evidence documenting the impacts our changing climate has on human health.⁴⁰ Rising temperatures and extreme weather events (including floods, hurricanes, droughts, and fires) have been associated with worsened health outcomes in multiple settings.^{41,42} In particular, these and other climate change-related exposures (CCEs) have been increasingly linked to worsened mental health⁴⁴, with systematic reviews suggesting, among other climate condition impacts, positive associations between high ambient temperatures and mental disorders,⁴⁵ drought conditions and suicide,⁴⁶ and cyclones and negative mental health outcomes.⁴⁷

Despite the weight of this evidence, few quantitative studies evaluating the effects of climate on population mental health have, to date, taken place in low- and middle-income countries (LMICs),⁴⁸ populations that—despite contributing the least to human-driven climate change—are among the most likely to be vulnerable to its impacts.⁴⁹

Among low-income countries most vulnerable to the health consequences of climate change is Madagascar, a nation that generates less than a tenth of a percentage of global carbon dioxide emissions. Worsening CCEs in Madagascar (primarily in the form of droughts, floods, and cyclones) are likely to exacerbate endemic, climate-sensitive threats to health, including malnutrition and malaria.⁵⁰ In particular, persistent drought conditions in recent years have led to extensive food insecurity.⁵¹ Though there is debate concerning the extent to which human activity is directly responsible for Madagascar's current drought,^{52,53} the extremity of the situation has led some observers to classify conditions in Madagascar as the first climate change famine in history.⁵⁴

Understanding how both incremental and extreme changes in climate impact population mental health is critical to gauging the full extent to which CCEs impact human health and wellbeing under a multidisciplinary approach to population health.⁵⁵ This understanding is particularly important

in contexts such as Madagascar, where climate conditions are already demonstrating pronounced pressures on economic, social, and physical wellbeing.

In this ecological study, we investigated the association of climate conditions and population mental health in Madagascar between 2010 and 2020 using routine health system data from Madagascar's Ministry of Public Health. The use of health system data enabled us to indirectly evaluate the extent to which existing public health data may already be showing signals of CCEs, which may aid efforts to prevent and mitigate mental health stressors and better design systemic responses to mental health needs. As a measure of population mental health, we considered facility-level monthly counts of new diagnoses of mental disorders. To capture the importance of both variation in temperature and precipitation conditions in Madagascar, we explored the predictive association of three climate conditions with incident mental health disorders: mean monthly ambient air temperature, mean monthly soil moisture, and monthly cyclone activity.

2.2 Methods

2.2.1 Data

To analyze the impact of climate on population mental health in Madagascar, we first obtained health management information system (HMIS) data from the Madagascar Ministère de la Santé Publique. We then obtained gridded temperature and soil moisture data from the European ReAnalysis (ERA5)⁵⁶ and the European Space Agency's Climate Change Initiative (ESA CCI),⁵⁷ respectively. Data on tropical storms and cyclones were obtained from open-source compilations of storms in the South-West Indian Ocean⁵⁸, which were in turn cross-referenced against storm trajectory data from the National Oceanic and Atmospheric Administration (NOAA)⁵⁹ for accuracy.

2.2.1.1 Outcomes Madagascar’s health information system provided facility-level data on counts of disease incidence summarized and reported monthly. Prior to 2019, this system was the Gestion du Système d’Information Sanitaire (GESIS); in early 2019, the system transitioned to using District Health Information Software 2 (DHIS2).

Among facilities reporting any mental health data between 2010 and 2020, data were obtained from 3,171 public and private primary health centers (known as Centres Santé de Base or CSBs and Formations Sanitaires Privées de Base or FSBs, respectively), 162 district referral hospitals (CHDs), 45 regional referral hospitals (CHRRs) and university hospitals (CHUs), for a total of 3,378 uniquely-identified facilities in our sample.

Exploratory data analysis indicated that the classification and reporting of counts of mental disorders in GESIS varied across types of facilities in their level of detail. Among CHD facilities, incidence of mental disorders was aggregated with neurological disorders (coded as “neuro psychiatric disorders”), while CHRR and CHU facilities reported more detailed counts of specific mental disorders, such as depression, personality disorders, and schizophrenia. Across all facilities, disaggregated data was reported by age group but not by sex. Among CSB facilities, incidences of mental disorders were reported by age group under “mental illnesses and psychic disorders” until June 2015, when reporting was reclassified to “mental disorders,” and disaggregated data was reported by both age and sex.

To address heterogeneity in reporting, our analysis aggregated any monthly incidence of mental or neurological disorders reported by a facility, irrespective of age and sex, into a summary outcome measure. To address outliers, monthly observations of the outcome were arranged separately for each facility into a unique time series. The nonparametric Friedman’s super smoother regression estimator⁶⁰ was applied to each time series to identify outlier observations and replace them through linear interpolation.⁶¹ By considering outliers on a facility-by-facility basis, the data cleaning

approach preserved extreme values that may reflect true variances in incidence (for example, incidences reported by a large, regional reference hospital) while addressing potential errors in data entry. (Additional detail on the data cleaning process is available in Appendix 2.1)

2.2.1.2 Geospatial data To retrieve spatial climate data for the facilities in our sample, it was first necessary to geocode facilities to obtain their latitude and longitude. Facility data from GESIS included limited geospatial information. While exact facility coordinates were not available, information on the relevant administrative unit served by a facility was included in the data (e.g., regions for CHRRs, districts for CHDs, and communes for CSBs). These data informed a stepwise matching process to locate facilities in our sample.

First, region, district, and commune names in our sample were standardized against reference shapefiles to address variations in translation, abbreviation, transposition, accent marks, spacing, hyphenation, and spelling. (A summary of the standardized names is provided in Appendix 2.2.) Next, facility names, types, and associated administrative units were used to match facilities to a validated spatial inventory of health facilities in Sub-Saharan Africa,⁶² of which 2,625 coordinates were provided for public facilities in Madagascar. In order to systematically match facilities in our sample to facilities in the spatial inventory, we implemented approximate string matching, which allowed for facility names and administrative units to be matched approximately, rather than exactly, to corresponding patterns in the validated spatial inventory. Applying this matching technique, 1,768 facilities (52%) in our sample were matched to validated coordinates.

Among the remaining facilities, an additional 827 primary facilities were matched to coordinates from a spatial inventory of 3,171 coordinates obtained from the Routine Health Information Network (RHINO),⁶³ which supports an open source database of health facility data in conjunction with the United States Agency for International Development, the government of Madagascar, and other

stakeholders.

To geolocate the remaining facilities, our existing inventories were combined with additional spatial inventories of health facility coordinates gathered from local consultants, the Global Healthsites Mapping Project, and other sources to create a database of 13,358 uniquely identified coordinates for potential matches. Using this database, an additional 414 facilities in our sample were geolocated using manual and approximate string matching.

An additional 257 facilities were matched to the centroid of their relevant administrative unit in cases where the unit was less than or equal to 225 square kilometers, as these administrative units are quite small relative to the spatial resolution of gridded climate data (approximately 900 km²). Among the remaining facilities, geolocations were manually identified for 112 facilities using targeted searches, resulting in 3,378 of the 3,378 facilities (100%) in the sample being geolocated.

To gauge the accuracy of the geolocating process, a subset of 1% of geolocated facilities was selected for validation against manually identified coordinates. Comparing the geolocated coordinates to validated coordinates for each facility, the mean distance between coordinates in the validation sample was 1.41 km., with a maximum distance of approximately 9.5 kilometers, indicating high accuracy in the geolocated process relative to the spatial resolution of climate data. Additional detail on the geolocating and validation process is available in Appendix 2.2.

2.2.1.3 Climate data Facility geolocations were then used to retrieve spatially referenced monthly averages of temperature and soil moisture data from ERA5 and ESA CCI, respectively. To allow for modelling of lagged associations, data were obtained for both ERA5 and ESA CCI SM from January 2008 to July 2020.

ERA 5 is a global atmospheric reanalysis from the European Centre for Medium-Range Weather Forecasts (ECMWF) and is freely available through its Copernicus Climate Change Service (C3S)⁵⁷.

The spatial resolution of ERA 5 is approximately 30 km., with quality-assured hourly estimates available from 1959 to the present⁵⁷. Using Google Earth Engine, a time series of monthly aggregate values for mean air temperature in degrees Kelvin at a height of 2 meters was obtained for each facility geolocation⁶⁴. Temperature data was then converted to degrees Celsius.

We obtained soil moisture data from the European Space Agency's soil moisture dataset (ESA CCI SM), the world's first and most comprehensive, multi-decade, satellite-observed dataset of global soil moisture. The spatial resolution of ESA CCI SM is approximately 26 km., with daily estimates available from 1978 to 2021. Using ESA CCI SM active and passive radiometer data, a time series of monthly aggregate values for mean soil moisture—measured as saturation percentage—was constructed from daily observations at each land grid point within Madagascar. We then applied nearest neighbor matching to link these time series to our geolocated facilities.

For a location to have soil moisture data available in ESA CCI SM, it must fall within one of 244,243 land grid points. For some facilities on Madagascar's coastline, their location placed them outside of ESA CCI's spatial coverage, resulting in missing values. To address facilities without any soil moisture data, nearest neighbor searching was conducted to identify the nearest land grid point for which ESA CCI SM data would be available; this nearest neighbor's soil moisture time series data would then be applied to the facility with missing data. Within a time series of ESA CCI data for a given location, however, monthly data could still be missing if adequate satellite observation was not recorded anytime during a given month; for these values, we used linear interpolation to address missing data within a time series.

In addition, we obtained data on tropical storms and cyclones in the South-West Indian Ocean for the 2009-2010 to 2020-2021 seasons, inclusive. Open source data on tropical cyclones in the south-west Indian Ocean was obtained by scraping information from Wikipedia summaries of each cyclone season, which were originally sourced from alerts issued by Météo-France La Réunion (MFR

La Réunion), the World Meteorological Organisation designated Regional Specialized Meteorological Centre (RSMC) for the provision of forecasts and warnings of tropical cyclones in the South-West Indian Ocean. To ensure that the compiled data accurately reflected storms in Madagascar during the study period, we cross-referenced these data against storm trajectory data for the South Indian Basin from NOAA.⁵⁹

With these data, we generated two indicators to measure exposure to storm activity in a given month: a binary indicator for whether a storm impacted Madagascar in that month and a count indicator for the number of days per month with a storm. To capture lingering post-dissipation effects, we defined impact as the storm's duration plus an additional 14 days.

2.2.2 Statistical analysis

All analyses were completed using R (version 4.2.1).³² Marginal effects were calculated using the ‘margins’ package (version 0.3.26)⁶⁵ for R.

2.2.2.1 Modeling approach Exploratory data analysis highlighted that the variance of monthly facility-level counts of incident mental disorders highly exceeded the mean; consequently, our statistical analysis utilized negative binomial (NB) regression, which is recommended in the case of over-dispersed count data.

Our primary analysis involved conducting four models to estimate the association between facility-level counts of incident mental disorders and climate conditions. Model 1 used temperature as the principal predictor of counts of incident mental disorders. Model 2 only used soil moisture as a predictor. Model 3 used both temperature and soil moisture independently as predictors, while Model 4—our preferred model—introduced an interaction term between the two.

Duration of cyclone activity was included in all models using our count indicator of exposure. In all models, we included fixed effects for Madagascar’s twenty-two regions to account for geographic

differences in climate patterns and case reporting. We further included month and year fixed effects to account for seasonality and time-varying omitted variables.

In addition, to aid in the interpretation of results, our analysis further reported the average marginal effect of each model predictor. Marginal effects clarify the effect of a per-unit change in a continuous explanatory variable (e.g., temperature) on an outcome where the regression model involves interaction. (In models without interaction or higher-order terms, the slope coefficient from the model will equal the marginal effect.) In addition to estimating the average marginal effects of our temperature, soil moisture, and cyclone variables, we further calculated the marginal effect and predicted values of the outcome for each unit of climate exposure across the three variables of interest.

To test for lagged associations—that is, whether in a given month, climate conditions in prior months were associated with counts of mental disorders—versions of Model 4 were conducted using lagged predictors. Measures of association were estimated for each monthly lag increment between 1 month and 18 months, inclusive.

Owing to the large number of observations in our sample, significance was evaluated against an alpha of 0.01, with 99% confidence intervals reported. Coefficients and confidence intervals for our indicators of climate exposure were exponentiated to generated incidence rate ratios (IRRs). Confidence intervals were constructed using heteroskedasticity-robust standard errors.

2.2.2.2 Subgroup analysis Madagascar is home to a diverse range of terrestrial ecoregions, each of which has unique physical, climatic, and ecological characteristics. These variations in the environment include distinct patterns of rainfall, temperature, and cyclone activity, potentially resulting in effect heterogeneity when examining how these exposures impact human health across different ecoregions.

To explore potential heterogeneity of our effect estimates, we evaluated Models 1 through 4 among facilities in each of Madagascar's four predominant ecoregions: the lowland, humid forests of the east, the subhumid forests of the Central High Plateau, the desert and xeric shrublands of the south, and the northeastern Dry deciduous forests. (Ecoregions are presented in Figure 4.)

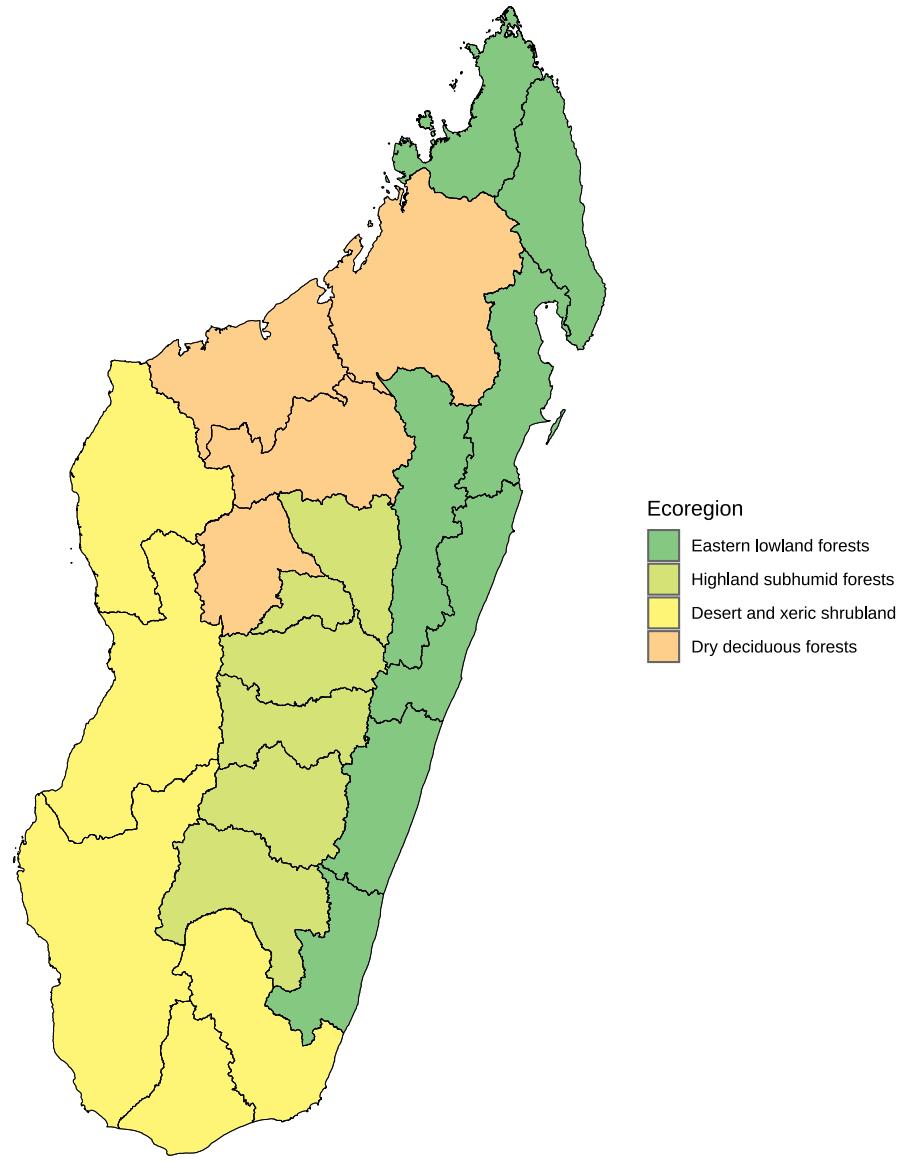


Figure 4: Predominant ecoregions of Madagascar, summarized by administrative region.

2.2.2.3 Sensitivity analysis In order to evaluate the robustness of our main results to alternative specifications, data processing, and modeling decisions, we generated 192 plausible model combinations to conduct a multiverse analysis to identify how sensitive effect estimates and confidence intervals were to different methodological choices.

To generate the model combinations, we first detailed seven methodological choices and their potential specifications. These criteria are outlined in Table 2.1.

Table 2.1: Alternative specifications, data processing, and modeling decisions for multiverse analysis.

*: preferred specification. CSB/FSP: Centres Santé de Base and Formations Sanitaires Privées de Base. NB: negative binomial model

1. Data cleaning for outcome data
a) Linear interpolation to replace outliers *
b) No adjustment (raw data)
2. Sample
a) Full sample *
b) Primary care facilities only (CSB/FSP)
3. Relationship of temperature and soil moisture
a) Additive model
b) Interactive model *
4. Regression framework
a) NB model *
b) Poisson model
5. Cyclone activity
a) Count indicator
b) Binary indicator
c) Excluded (i.e., no indicator)
6. Month and year fixed effects
a) Included *
b) Excluded
7. Regional fixed effects
a) Included *
b) Excluded

First, we considered the role of data cleaning in the outcome data and chose to compare our analysis using the cleaned outcome data against the raw, unadjusted values. Second, we chose to compare our findings using data from all facilities (the full sample) against a sample without district and regional hospital (CSB/FSP facilities only). Primary care facilities have smaller catchment areas than hospitals; consequently, it is more plausible that climate data for primary care facilities will closely reflect climate exposure to patients compared to referral hospitals. Third, we considered the decision to model temperature and soil moisture as an additive or interactive relationship (Model 3 vs. Model 4), with both alternatives included in our multiverse analysis. Fourth, we evaluated our decision to account for overdispersion with a NB model by using a Poisson regression framework as an alternative. Fifth, we evaluated alternative specifications of exposure to cyclone activity, using three options: our binary indicator, our count indicator, and no term for cyclone activity included. Sixth, we toggled whether time fixed effects (month and year) were included. Seventh, we similarly toggled regional fixed effects.

We then interacted the methodological choices to generate 192 plausible models. Using the effect estimates and confidence intervals for these models, we constructed specification curves for monthly temperature, soil moisture, and—for the 64 models that included the cyclone count indicator—cyclone activity to visually compare the distribution of plausible estimates under different combinations.

2.2.2.4 Ethics statement The Institutional Review Board (IRB) of the Harvard T.H. Chan School of Public Health determined that the study was not human subjects research, and that additional review was not required (protocol number: IRB21-1303, determined on October 19, 2021).

2.3 Results

Our geolocated sample of facilities—which is displayed in Figure 5—showed geographic diversity and comprehensive coverage across Madagascar, with most geolocations identified through validated sources.

Figure 6 shows the spatial distribution of temperature and soil moisture across the facilities in our sample during January and June 2015, corresponding to the warmer, wet season and the dryer, cool season, respectively. When evaluated over time, annual climate trends in Madagascar showed relatively stable distribution of average temperatures, while soil moisture had a slight upward shift through 2020 (Figure 7). Data of tropical storm and cyclone activity throughout the study period also exhibited seasonal patterns, with most major storms occurring in the hot season, with a peak between February and May (Figure 8).

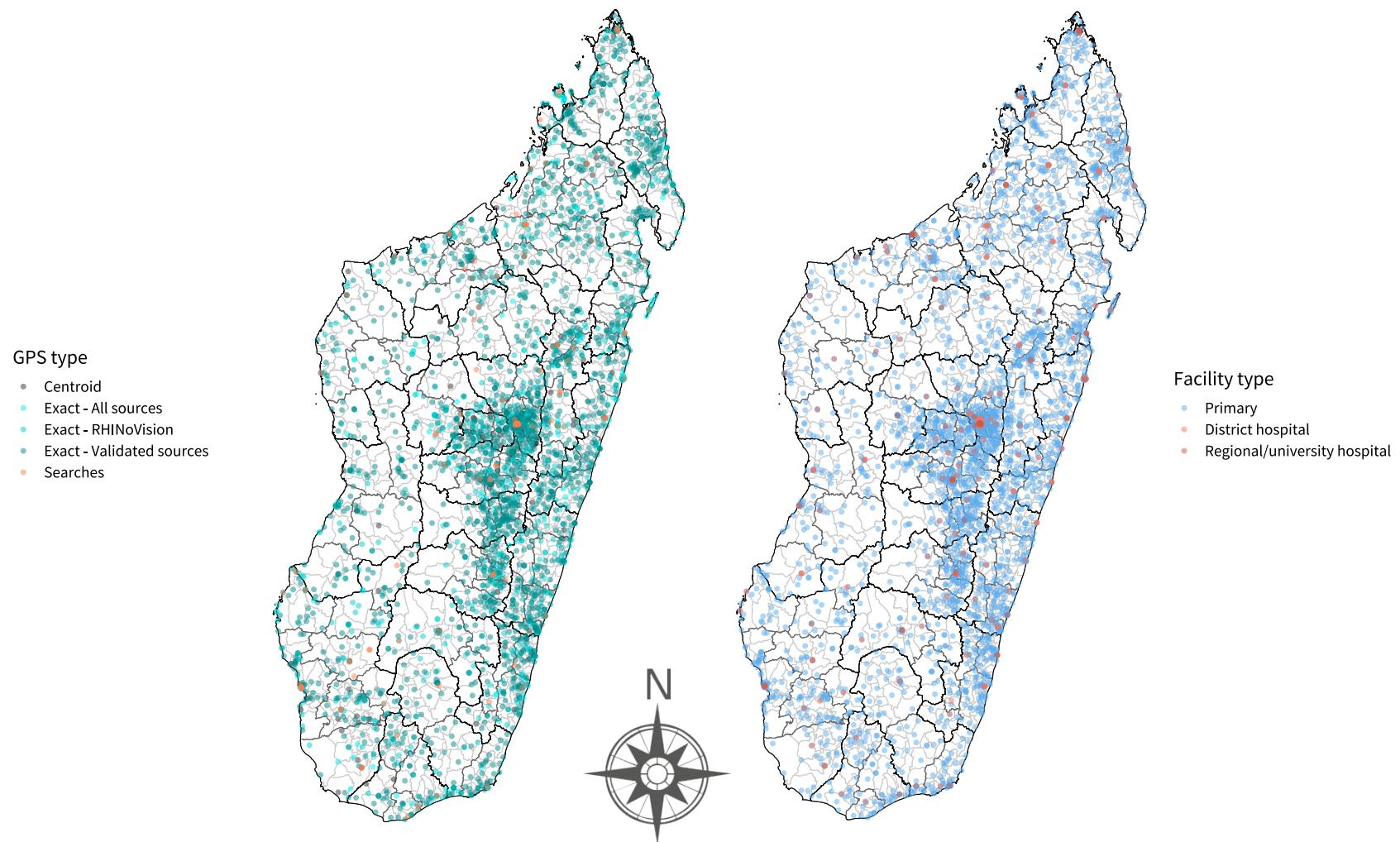


Figure 5: Map of facilities in Madagascar, by GPS coordinate source (left panel) and facility type (right panel).

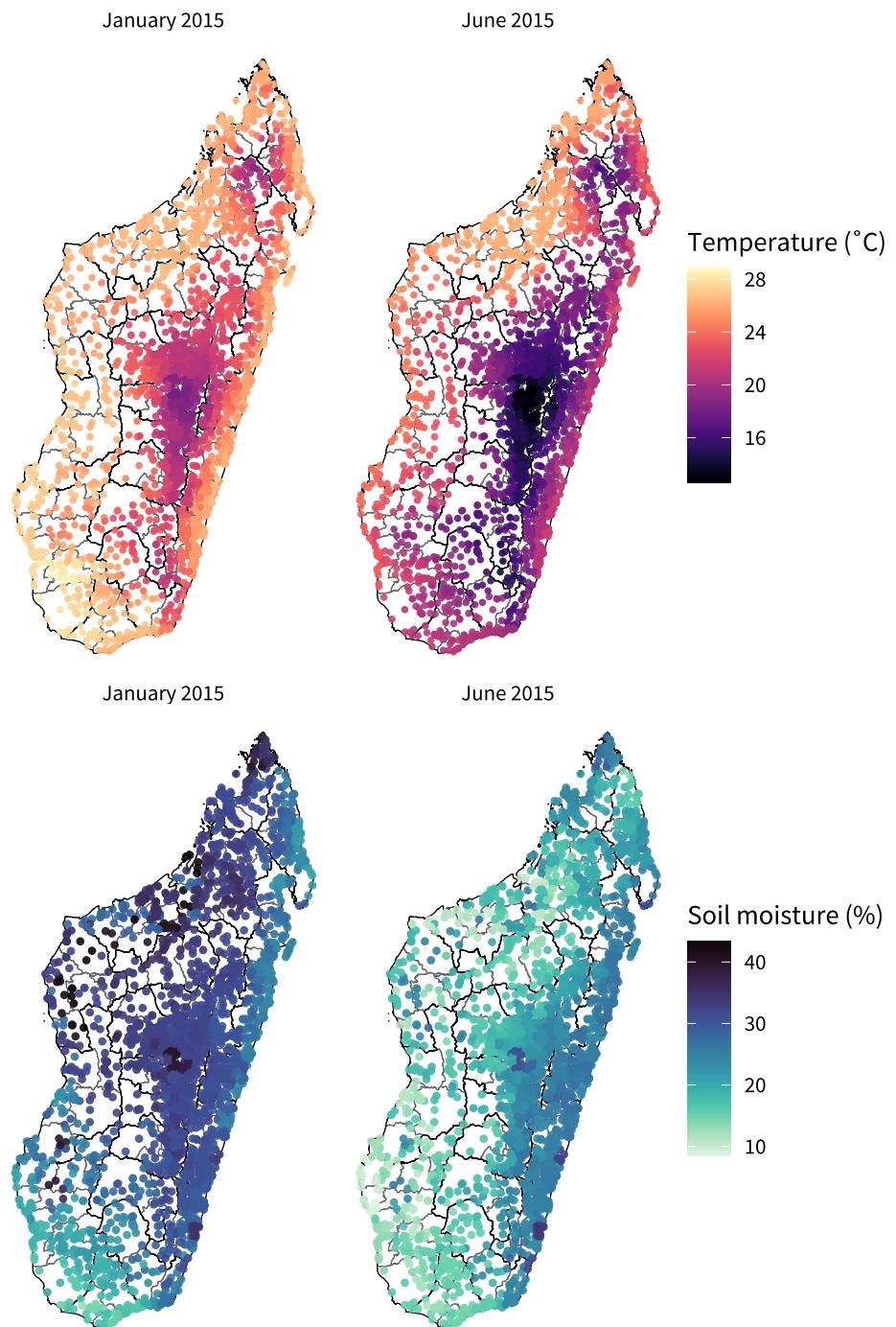


Figure 6: Spatial distribution of climate conditions across clinics and seasons in Madagascar. Mean monthly temperature (top) is measured in degrees Celcius and mean soil moisture is measured in percent saturation (below).

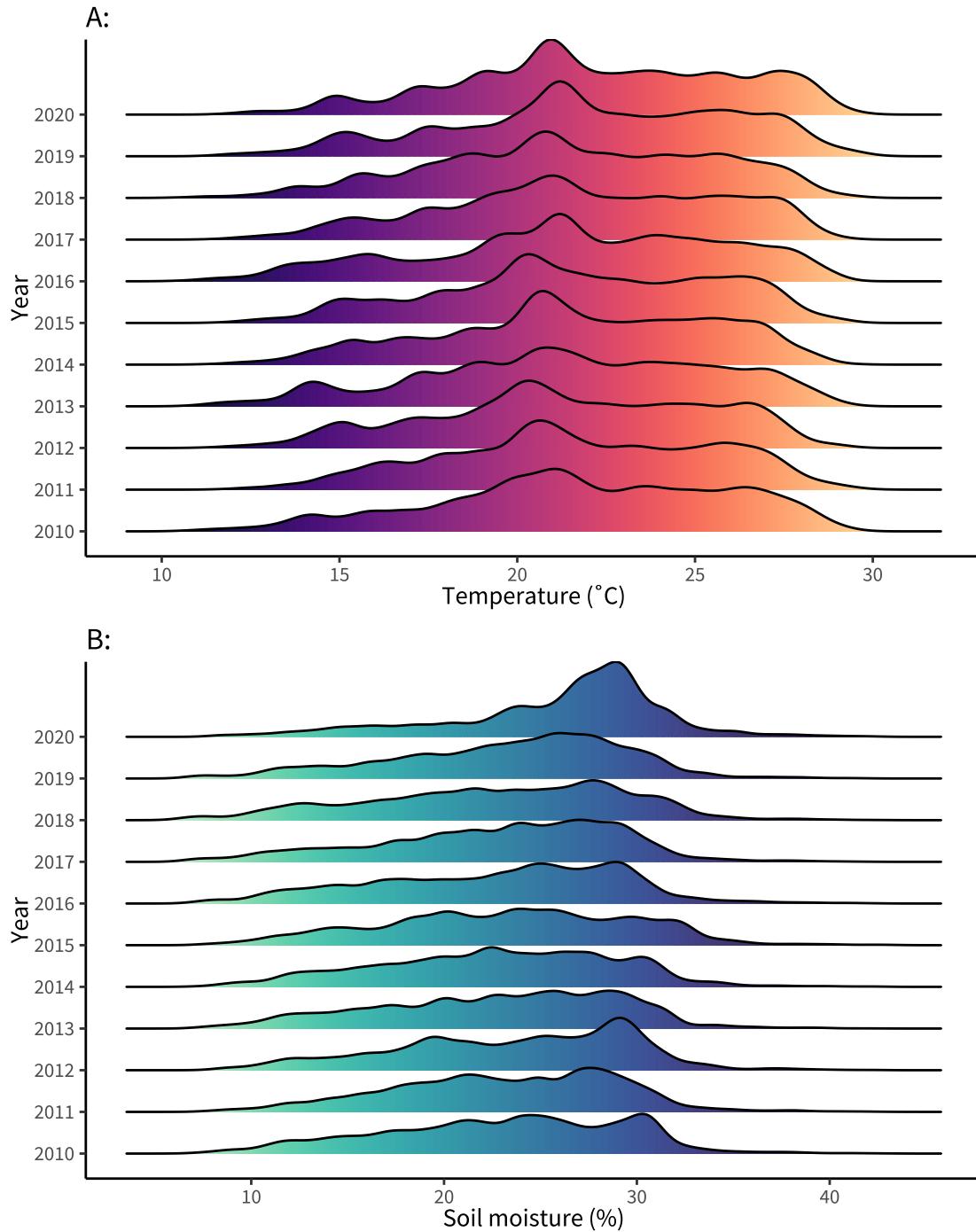


Figure 7: Distribution of A) temperature and B) soil moisture across all month-years and all clinics.

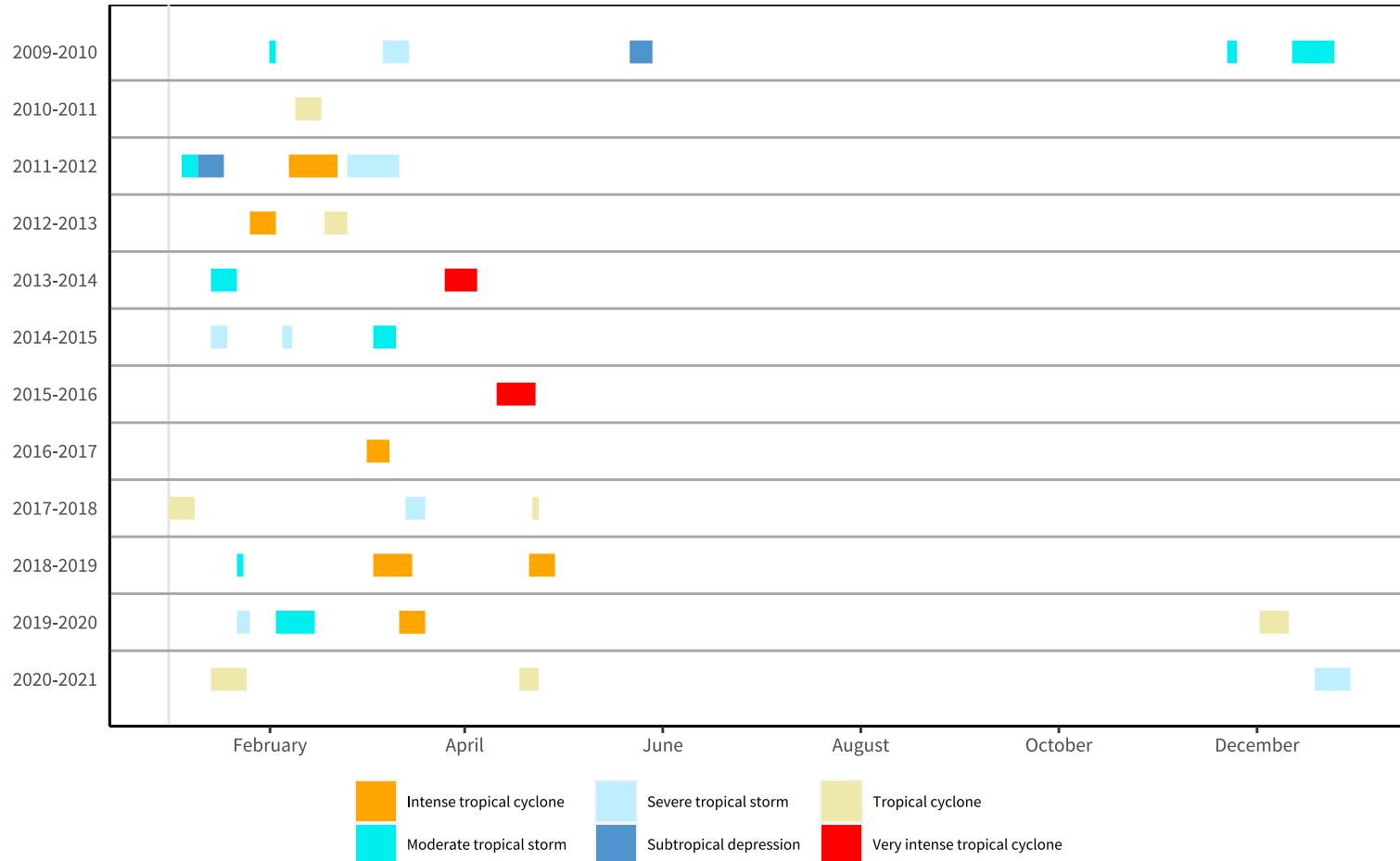


Figure 8: Tropical storms and cyclones in Madagascar by intensity and season, 2009-2010 to 2020-2021, inclusive.

Table 2.2: incidence rate ratios (IRRs) and average marginal effects (AME) from Models 1 through 4.

	IRR (99% CI)	M.E. (99% CI)
<hr/>		
Model 1 ^{a,b}		
Temperature	0.954 (0.934 – 0.973)***	-2.26 (-3.3 – -1.23)***
Cyclone (count)	0.995 (0.987 – 1)	-0.248 (-0.536 – 0.04)*
<hr/>		
Model 2 ^{a,b}		
Soil moisture	0.999 (0.985 – 1.01)	-0.0677 (-0.574 – 0.438)
Cyclone (count)	0.995 (0.987 – 1)	-0.264 (-0.559 – 0.0311)*
<hr/>		
Model 3 ^{a,b}		
Temperature	0.944 (0.923 – 0.965)***	-2.77 (-3.88 – -1.65)***
Soil moisture	0.991 (0.976 – 1.01)	-0.454 (-0.986 – 0.0782)*
Cyclone (count)	0.994 (0.986 – 1)*	-0.296 (-0.59 – -0.00168)**
<hr/>		
Model 4 ^{a,b}		
Temperature	0.958 (0.909 – 1.01)*	-2.85 (-3.98 – -1.72)***
Soil moisture	1.01 (0.958 – 1.06)	-0.354 (-0.966 – 0.258)
Temperature X Soil moisture	0.999 (0.997 – 1)	
Cyclone (count)	0.994 (0.986 – 1)*	-0.3 (-0.595 – -0.0055)**

^aAll models include month, year, and regional fixed effects.

^b*** p < 0.001, ** p < 0.01, * p < 0.05

2.3.1 Main analysis

The regression models predicting monthly counts of any mental or neurological disorder (Table 2.2) showed significant associations with temperature across all models. A one-degree Celsius increase in temperature was associated with approximately 4.6% fewer cases reported (IRR: 0.954, $p < 0.0001$, 99% CI: 0.934 – 0.973) by primary clinics and hospitals in Model 1. Inclusion of both climate predictors resulted in little change to the measure of association for temperature. In an additive model with soil moisture included (Model 3), the effect estimate associated with temperature grew to 5.6% fewer cases reported (IRR: 0.944, $p < 0.0001$, 99% CI: 0.923 – 0.965). Adopting an interactive model (Model 4) attenuated the association (IRR: 0.958, $p = 0.038$, 99% CI: 0.909 – 1.01), but remained significant at a 95% level of confidence. Across all models with temperature, the average marginal effect associated with temperature (across a sample with all clinics) ranged between 2 and 3 fewer monthly cases reported and was statistically significant at an alpha of 0.01, with the average marginal effect in Model 4 being -2.85 cases ($p < 0.001$, 99% CI: -3.976 – -1.719).

Effect estimates associated with soil moisture were not statistically significant across all four models. In all models, we observed a modest reduction in cases reported per each additional day duration of cyclone activity, with the incidence ratio ratios of Models 3 (IRR: 0.994, $p = 0.047$, 99% CI: 0.986 – 1.002) and Models 4 (IRR: 0.994, $p = 0.047$, 99% CI: 0.986 – 1.002) being significant at a level of 0.05. In all models, however, the average marginal effect was close to 0, with the average marginal effect in Model 4 being only -0.3 cases ($p = 0.009$, 99% CI: -0.595 – -0.006).

Predicted values of monthly case counts under Model 4 echoed the effect estimates from Table 2, with fewer cases reported in warmer months (Figure 9). Marginal effect estimates across the distribution of temperatures in our data showed that the greatest level of reduction occurred between 10 and 15 degrees Celsius, with each degree increase associated with 4 to 5 fewer cases of mental or neurological disorders reported, controlling for other covariates. Months with greater levels of soil

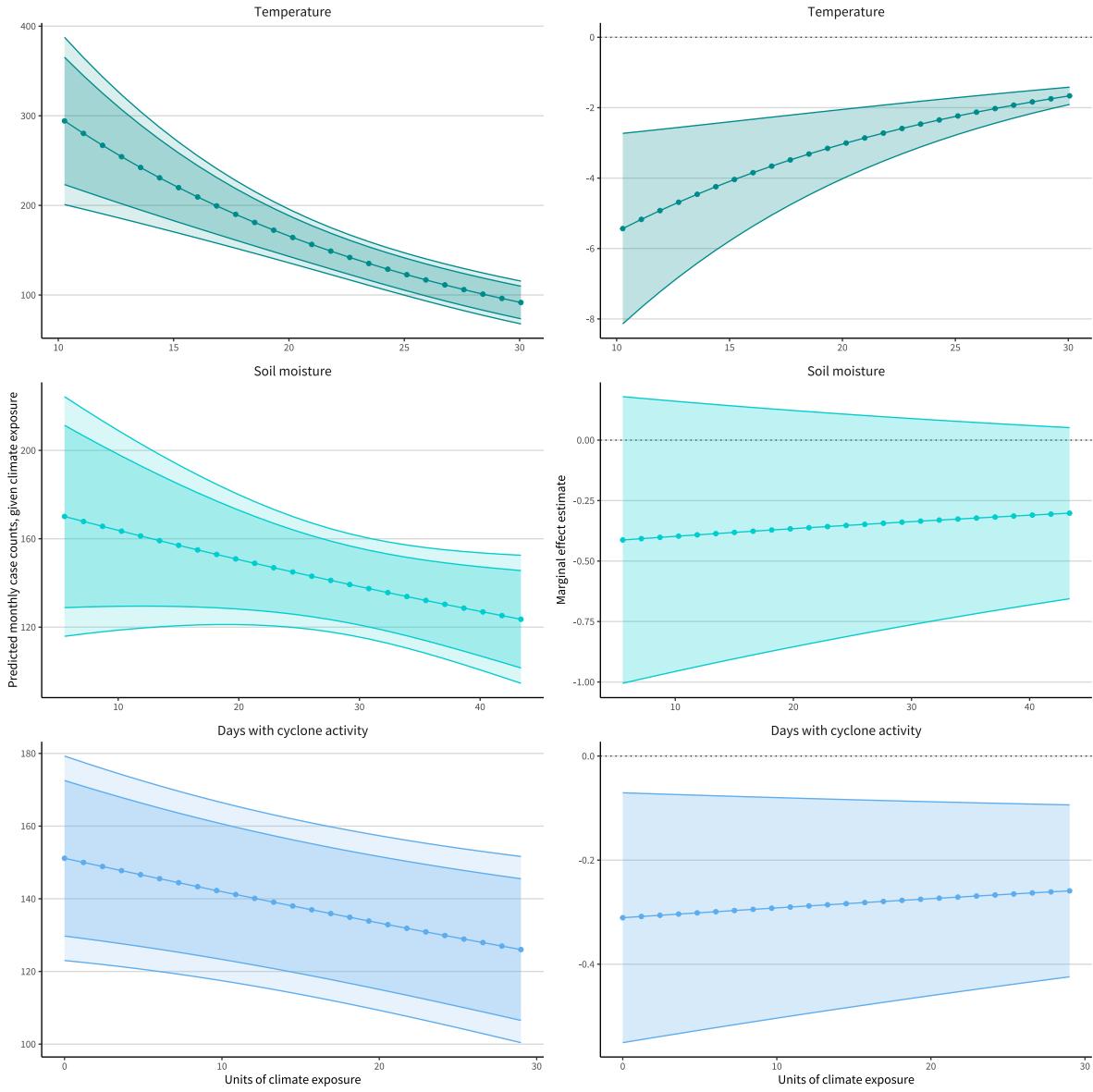


Figure 9: Predicted values of monthly case counts and marginal effect estimates by coefficient and their 95% and 99% confidence intervals. The left panels show predicted values of monthly case counts of mental and neurological disorders in Madagascar, given different units of climate exposure. The right panels show marginal effect estimates over different units of climate exposure in the data. The dotted horizontal lines in the right panel depict no marginal effect on case counts. In all panels, the model used to generate predictions and marginal effects corresponds to Model 4. Units of climate exposure are degrees Celsius for temperature (top), saturation percentage for soil moisture (middle), and days with cyclone activity (bottom).

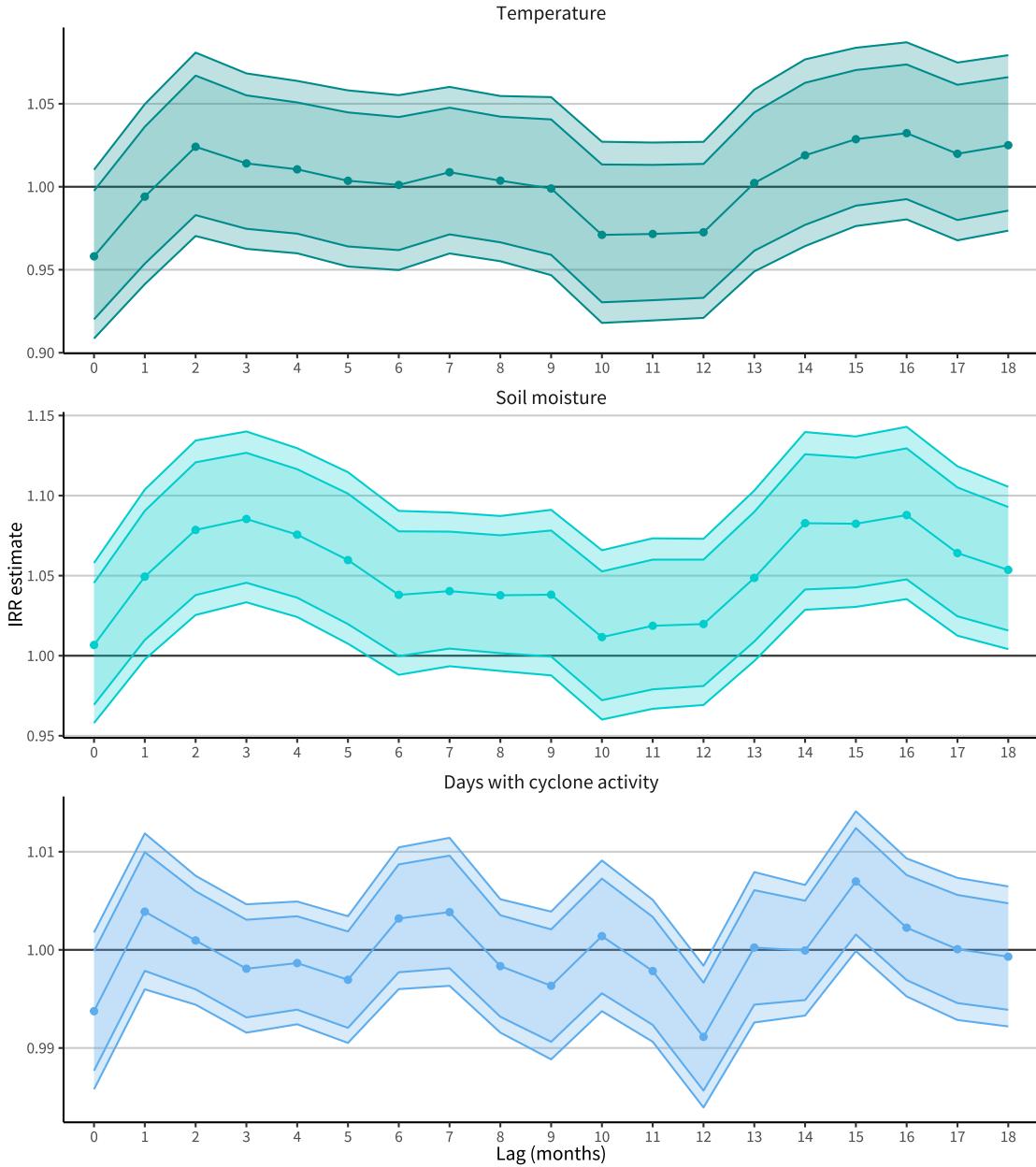


Figure 10: Effect estimates by coefficient with lagged exposures and their 99% and 95% confidence intervals, Model 4. The x-axis correspond to the length of the lag (e.g., a value of 2 reflects a lag of two months, such that case counts are predicted by climate conditions two months prior), with the value of 0 reflecting a model without any lag in exposure. The dotted horizontal lines depict a null effect. IRR: incidence rate ratio.

moisture and days with cyclone activity also showed fewer reported cases; however, the marginal effects associated with soil moisture were not significant across any unit of exposure, while those associated with days with cyclone activity were close to zero for all lengths of activity.

Examining lagged effects showed potential temporal associations between soil moisture levels in preceding months and case counts in those following (Figure 10), with higher saturation leading to a statistically significant elevation in cases reported 1 to 5 months later. At a lag of 3 months, the elevation in cases was approximately 8.5% (IRR: 1.085, $p < 0.0001$, 99% CI: 1.046 – 1.127). There appeared to be a significant elevation of similar magnitude 13 to 17 months prior, suggesting potential annularity in lagged association. Effects for temperature were not significant across any lag; cyclone activity similarly showed no significance in lags under a year, but did show modest, statistically significant associations at lags of 12 months (IRR: 0.991, $p = 0.002$, 99% CI: 0.986 – 0.997) and 15 months (IRR: 1.007, $p = 0.011$, 99% CI: 1.002 – 1.012). A slight increase in cases was associated with cyclone activity in a prior month, but this increase was not statistically significant (IRR: 1.004, $p = 0.206$, 99% CI: 0.998 – 1.01).

2.3.2 Subgroup analysis

Results from our subgroup analysis showed evidence of potential effect heterogeneity by ecoregion (Table 2.3). For temperature, estimates of association were only statistically significant in the highland subhumid forests, where each one-degree Celsius increase in temperature was associated with 25.2% fewer cases reported (IRR: 0.748, $p < 0.0001$, 99% CI: 0.632 – 0.885). Temperature was associated with a slight increase in temperature in the eastern lowland forests (IRR: 1.016, $p = 0.785$, 99% CI: 0.875 – 1.18) and the desert and xeric shrublands (IRR: 1.016, $p = 0.785$, 99% CI: 0.875 – 1.18), but in neither case was the estimate significant at a level of 0.05.

Table 2.3: subgroup analysis results, summarized by incidence rate ratios (IRRs) and average marginal effects (AME) from Models 1 through 4.

	IRR (99% CI)	M.E. (99% CI)
Temperature ^{a,b}		
All	0.958 (0.909 – 1.01)*	-2.85 (-3.98 – -1.72)***
Eastern lowland forests	1.02 (0.875 – 1.18)	-0.525 (-1.84 – 0.795)
Highland subhumid forests	0.748 (0.632 – 0.885)***	-17 (-21.5 – -12.4)***
Desert and xeric shrubland	1.02 (0.847 – 1.23)	0.898 (-0.716 – 2.51)
Dry deciduous forests	1 (0.9 – 1.11)	-2.67 (-4.24 – -1.11)***
Soil moisture ^{a,b}		
All	1.01 (0.958 – 1.06)	-0.354 (-0.966 – 0.258)
Eastern lowland forests	1.11 (0.966 – 1.27)	2.77 (1.8 – 3.74)***
Highland subhumid forests	0.859 (0.754 – 0.979)**	-7.18 (-9.53 – -4.83)***
Desert and xeric shrubland	0.872 (0.688 – 1.11)	-1.69 (-2.25 – -1.13)***
Dry deciduous forests	1.22 (1.08 – 1.37)***	3.49 (2.35 – 4.63)***
Temperature X Soil moisture ^{a,b}		
All	0.999 (0.997 – 1)	
Eastern lowland forests	0.999 (0.993 – 1)	
Highland subhumid forests	1 (0.996 – 1.01)	
Desert and xeric shrubland	1 (0.992 – 1.01)	
Dry deciduous forests	0.996 (0.992 – 1)*	
Cyclone (count) ^{a,b}		
All	0.994 (0.986 – 1)*	-0.3 (-0.595 – -0.0055)**
Eastern lowland forests	0.992 (0.981 – 1)	-0.288 (-0.69 – 0.115)
Highland subhumid forests	0.997 (0.985 – 1.01)	-0.248 (-1.05 – 0.549)
Desert and xeric shrubland	0.999 (0.979 – 1.02)	-0.0146 (-0.317 – 0.288)
Dry deciduous forests	0.986 (0.971 – 1)*	-0.457 (-0.951 – -0.0362)*

^aEstimates from Model 4 (interactive model), which include month, year, and regional fixed effects.

^b*** p < 0.001, ** p < 0.01, * p < 0.05

With respect to soil moisture, while our primary analysis found no evidence of a statistically significant association with reported cases in the full sample, we did find evidence of heterogeneity in our subgroup analysis. Among facilities in the highland subhumid forests, we found that each percentage point increase in soil moisture was associated with 14.1% fewer reported cases (IRR: 0.859, $p = 0.003$, 99% CI: 0.754 – 0.979), with an average marginal effect of -7.18 reported cases ($p < 0.001$, 99% CI: -9.527 – -4.83). Conversely, each percentage point increase in soil moisture in the dry deciduous forests was associated with a 21.6% increase in reported cases (IRR: 1.216, $p < 0.0001$, 99% CI: 1.077 – 1.373), with an average marginal effect of 3.49 reported cases ($p < 0.001$, 99% CI: 2.35 – 4.631).

Finally, our estimates of the incidence rate ratio associated with each additional day of cyclone duration in a given month were consistent between each ecoregion and our full sample. Among facilities in the dry deciduous forests, each additional day of cyclone activity was associated with the greatest reduction in reported cases (IRR: 0.986, $p = 0.016$, 99% CI: 0.971 – 1.001).

2.3.3 Multiverse analysis

In our multiverse analysis, 157 of 192 models (82%) returned effect estimates for temperature associating a one-degree increase with fewer reported cases of mental or neurological disorders, with 115 (60%) of those estimates having p-values below 0.01 (Figure 11). Only 6 (3%) models returned statistically significant IRR estimates greater than 1; all six models were negative binomial interactive models that excluded month and year fixed effects and were run on data that restricted to the CSB/FSP sample only.

With respect to soil moisture, only 65 of 192 models (34%) returned effect estimates with p-values below 0.01, with 40 of such models reporting IRRs greater than 1 and 25 models reporting IRRs smaller than 1 (Figure 12). The overwhelming majority of models showed no significant association

between soil moisture and monthly case counts, in either direction. Of models showing statistically significant IRRs of a magnitude greater than 1, all excluded both region and time fixed effects.

Among the 64 models that included cyclone activity measured in days per month, 58 models (91%) reported reduced case counts associated with cyclone duration, compared to 6 models (9%) showing IRRs below 1 (Figure 13). None of the 64 models, however, had a p-value below 0.01.

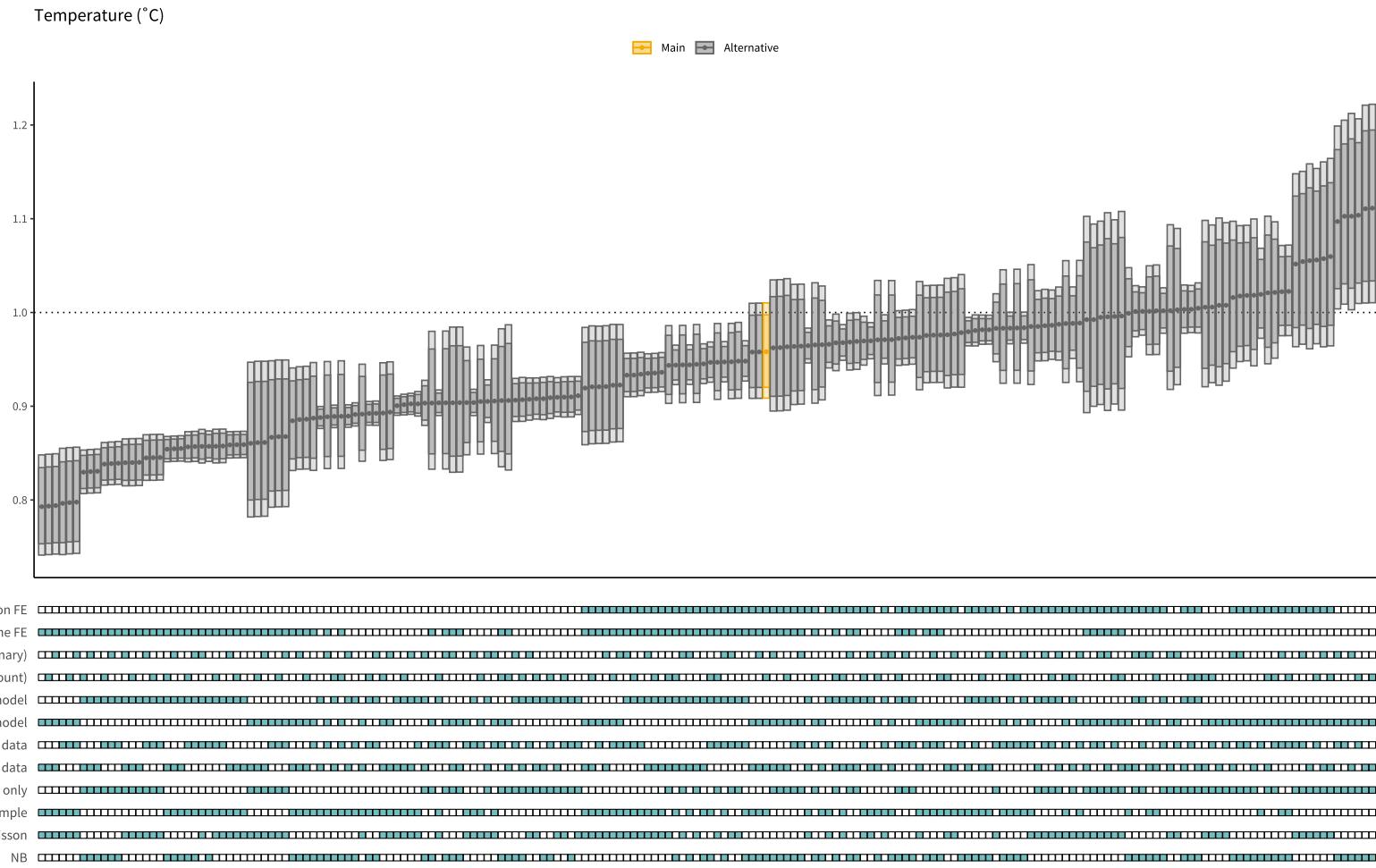


Figure 11: Specification curve depicting the effect estimates and confidence intervals for mean monthly temperature (degrees Celsius) across 192 models. In the top panel, estimated incidence rate ratios (IRRs) across different models are depicted as circles; the darkly and lightly shaded regions above and below these circles correspond to 95% and 99% confidence intervals of these estimates, respectively. The dotted horizontal line depicts a null effect. The IRR estimate and confidence intervals of the preferred model, Model 4, are highlighted in orange. Below each model, a legend of shaded and unshaded boxes indicates which modeling decisions correspond to a given model, with boxes shaded teal showing active features. FE: fixed effects. CSB/FSP: Centres Santé de Base and Formations Sanitaires Privées de Base. NB: negative binomial model.

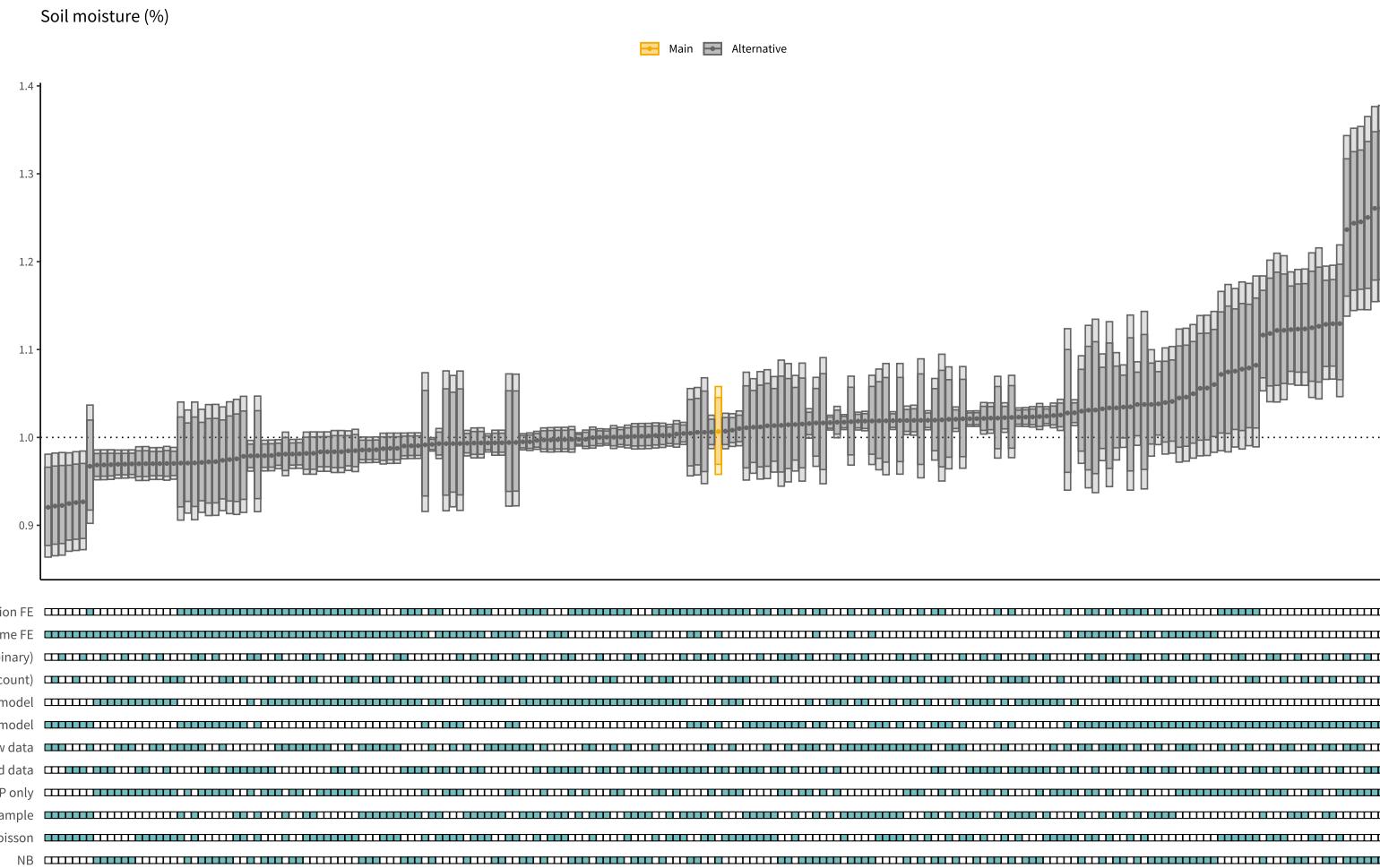


Figure 12: Specification curve depicting the effect estimates and confidence intervals for mean monthly soil moisture (percent saturation) across 192 models. In the top panel, estimated incidence rate ratios (IRRs) across different models are depicted as circles; the darkly and lightly shaded regions above and below these circles correspond to 95% and 99% confidence intervals of these estimates, respectively. The dotted horizontal line depicts a null effect. The IRR estimate and confidence intervals of the preferred model, Model 4, are highlighted in orange. Below each model, a legend of shaded and unshaded boxes indicates which modeling decisions correspond to a given model, with boxes shaded teal showing active features. FE: fixed effects. CSB/FSP: Centres Santé de Base and Formations Sanitaires Privées de Base. NB: negative binomial model.

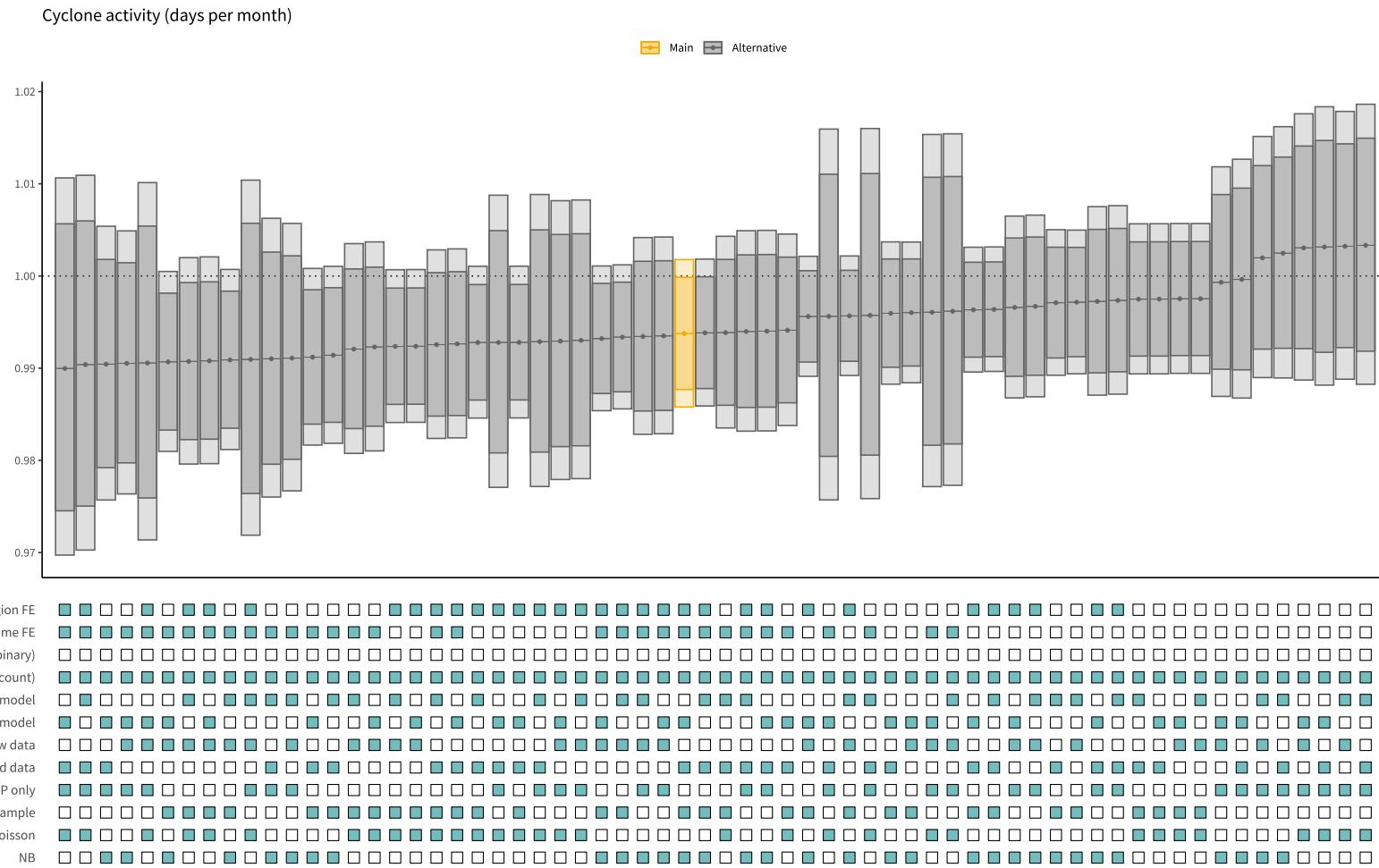


Figure 13: Specification curve depicting the effect estimates and confidence intervals for cyclone activity (measured as days with a tropical storm or cyclone impacting Madagascar in a month) across 64 models. In the top panel, estimated incidence rate ratios (IRRs) across different models are depicted as circles; the darkly and lightly shaded regions above and below these circles correspond to 95% and 99% confidence intervals of these estimates, respectively. The dotted horizontal line depicts a null effect. The IRR estimate and confidence intervals of the preferred model, Model 4, are highlighted in orange. Below each model, a legend of shaded and unshaded boxes indicates which modeling decisions correspond to a given model, with boxes shaded teal showing active features. FE: fixed effects. CSB/FSP: Centres Santé de Base and Formations Sanitaires Privées de Base. NB: negative binomial model.

2.4 Discussion

In our study of health facilities in Madagascar, we investigated how temperature, soil moisture, and exposure to cyclone activity impacted monthly incident cases of mental and neurological disorders reported by 3,378 facilities between 2010 and 2020. We found evidence of a statistically significant reduction in reported cases associated with mean monthly temperature, with warmer temperature being, on average, associated with 2 to 3 fewer cases per month. According to our multiverse analysis, the statistically significant inverse association we observed was robust to numerous specifications, while our subgroup analysis indicated that this association was primarily localized in the highland subhumid forest ecoregion.

With respect to soil moisture, we found evidence to suggest potential lagged impacts, with higher soil saturation being associated with an 8.5% elevation in reported case counts in the subsequent quarter. We also found evidence of possible effect heterogeneity, with each percentage point increase in soil moisture leading to an *elevation* of cases in the dry deciduous forest ecoregion (IRR: 1.216, p < 0.0001, 99% CI: 1.077 – 1.373) and a *decrease* in cases in the highland subhumid forests (IRR: 0.859, p = 0.003, 99% CI: 0.754 – 0.979).

Finally, while our lagged models and multiverse analysis suggested the possibility of a negative relationship between cyclone activity and incident case counts reported in Madagascar, the marginal effects associated with cyclone duration were negligible, and we did not observe sufficient statistically significant evidence to reject the null assumption of no association at a level of 0.01.

It is important to note in our interpretation of these findings that the true relationship between reported mental health cases and actual cases of mental disorders is not well understood, particularly in Madagascar where data on disease etiology is limited. The changes in reported cases could reflect changes in the actual cases of mental disorders, but could also result from changes in help-seeking behavior, diagnostic capacity, or other factors. Additionally, it is widely recognized that a

significant proportion of individuals with mental disorders do not receive any treatment, particularly in low-income settings.

With these caveats in mind, our results concerning an inverse relationship between temperature and recorded cases of mental and neurological disorders are nonetheless surprising and run counter to our expectation, given that a robust body of literature has documented that heat and heat waves have a harmful effect on mental health outcomes⁶⁶ and general aspects such as mood,⁶⁷ life satisfaction,⁶⁸ and happiness.⁶⁹

Research in subtropical regions, however, has found that the association between temperature and mental disorders is likely non-linear, with both extreme cold and extreme heat being associated with harmful effects on mental morbidity.⁷⁰ Degree increases in temperature, therefore, could show a protective effect in colder months, resulting in an overall inverse association between temperature and reported cases in a sample with few extremely warm months. This is consistent with our marginal effect estimates, which show the greatest reduction in case counts being associated with degree increases at the coldest temperatures. In addition, this explanation would be consistent with our subgroup analysis, which found that the protective effect of warmer temperatures was observed only among facilities in the central high plateau—where temperatures are generally cooler than those in the surrounding lowlands.

An alternative explanation could be that access to mental health services is limited in warmer months due to factors such as increased demand for medical services related to heat-related illnesses. A crowding out of provider availability due to physical complaints in warmer months (for example, malaria-related fever) could lead to decreased availability of provider access for mental disorders, especially at primary health facilities with already limited diagnostic capacity. Understanding how climate conditions in Madagascar impact the broader burden of disease, including physical conditions, is the subject of current investigation, and will lend further insight into potential

mechanistic explanations for our findings.

With respect to soil moisture, to the best of our knowledge, there have been no studies that directly explore the association between soil saturation and mental health in non-emergency conditions. In terms of extremely low soil moisture, evidence from droughts suggest potential indirect pathways to worsened mental health outcomes,⁷¹ but these impacts are not well characterized and may not manifest over a short time horizon.⁷²

Though incidence rate ratios and marginal effect estimates associated with soil moisture were not statistically significant in our main analysis, we did observe a significant association of higher soil moisture and cases of mental health complaints in the following quarter, echoing similar findings from U.S. meteorological data linking higher precipitation with worsened mental health.⁷³ In addition, our subgroup analysis also indicated significant and diverging effects among different ecoregions. In particular, we found that greater soil moisture was associated with higher cases reported in the eastern lowlands and the northern dry deciduous forests, which echoes the geographic concentration of flood risk in Madagascar.⁷⁴ Conversely, the observed (though statistically modest) reduction in cases associated with higher soil moisture in the desert and xeric shrublands overlaps with the concentration of drought risk, where increased soil moisture could be taken as an indicator of reduced drought vulnerability. It is important to note, however, that the time frame of available GESIS data excludes the most severe period of the ongoing drought in Madagascar, limiting our ability to directly study the impact of the current crisis on population mental health in this analysis. Further research could leverage spatial reanalysis data on precipitation to further characterize these associations.

Madagascar's wet season is marked by frequent tropical storms and cyclones—the intensification of which has been linked to rising temperatures in the Indian Ocean.⁷⁵ In the majority of our models in the multiverse analysis, we found that months with greater duration of cyclone activity were

associated with *fewer* monthly report cases of mental disorders, though none of these models were significant at the threshold of 0.01. In numerous studies, cyclones and similar disasters have been found to worsen mental health;⁷³ however, these storms may also result in numerous conditions that make access to mental health resources more challenging. Disruptions to regular health care services and an intensification of acute health needs⁷⁶ in the post-disaster period could result in barriers to receiving care for incident mental disorders,⁷⁷ which would be consistent with a reduction in reported cases despite a rise in mental distress.

Failure to observe effect heterogeneity in our subgroup analysis of the association of cyclone activity with reported case counts likely is due, in part, to our specification choice to define exposure to cyclone activity without geographic variation in intensity. While we felt justified in opting for a simplified indicator, given that storms in Madagascar typically impact the whole of the island, a more nuanced (but data-hungry) approach could define exposure with greater geographic precision based on additional climate metrics, including peak wind, rainfall, and distance from the storm's track.⁷⁸

A further weakness of our analysis is that inherent to any ecological study relying on aggregated data: the lack of individual-level data substantively constraints our ability to draw causal inferences, account for and exclude potential confounding variables, and ascertain mechanistic explanations for observed associations. While these are important caveats in interpreting our results, we assert that there is considerable value in leveraging existing data from national health management information systems to generate epidemiologic evidence. The opportunity to employ health information system data is particularly important in countries like Madagascar, where, as in many LMICs, HMIS information is routinely generated but systematically underutilized.⁷⁹

Despite these limitations, our analysis brings together health data from over three thousand health facilities over ten years, utilizing the most comprehensive sources of climate data available,

and linking the two via a rigorous, multistep geolocating process. This study—one of the only to investigate mental health and climate in Africa using national HMIS data—underscores the need for further research to understand the relationships and pathways between changing climate and population mental health.

2.5 Acknowledgements

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2.5.1 Author contributions

All authors contributed to study conception, methodology, and interpretation. DA oversaw data acquisition, programming, formal analysis, visualization, and the first draft of the manuscript. All authors had access to and verified all the data and accept responsibility for the decision to submit for publication.

2.5.2 Funding statement

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2.5.3 Declaration of interests

We declare no competing interests.

2.5.4 Data sharing statement

All codes used for the analysis in this article are available on GitHub (https://github.com/darias5/madagascar_mh).

3 The impact of COVID-19 vaccine developments on Google COVID-19 search trends for mental health symptoms: a controlled interrupted time series analysis

Daniel Arias, Jessica Cohen, Karestan Koenen, Margaret McConnell, Stéphane Verguet

Background: A key obstacle to studying the effects of public health responses on population mental health in the US is a lack of daily surveillance data on mental health indicators. A potential marker of population mental health is the use of Internet search data, which offers the potential for real-time, large-scale analysis and identification of evolving mental health issues.

Methods: We utilize controlled interrupted time series (CITS) approach to evaluate whether the development and announcement of safe and effective COVID-19 vaccines reduced Google searches related to symptoms of depression and anxiety. By comparing how search trends changed in the post period for mental health symptoms above and beyond changes observed in the same period for physical health symptoms, we estimate measures of association between the vaccine announcement and changes in mental health symptom search density. We adjust for state, month, and day of week effects, and we apply a sensitivity analysis to assess the robustness of our estimates to alternative specifications. We further examine whether estimates varied among states and counties that predominantly voted for the Democratic Party candidate in the 2020 presidential election compared to the Republican candidate.

Findings and interpretation: Under our main specification, we find evidence of reduced search density associated with the announcement of vaccine safety data for Google search trends for depression and anxiety. For searches related to depression, we observe a statistically significant slope change of -0.0304 percentage points per day ($p < 0.0001$, 99% CI: -0.0321– -0.0286) and a level shift of -0.184 ($p < 0.0001$, 99% CI: -0.226– -0.143), above and beyond changes in slope and

level observed for searches for headaches. For anxiety, we observe a similar slope change decline of 0.0383 percentage points per day ($p < 0.0001$, 99% CI: -0.0400– -0.0366) and a level shift of -0.339 ($p < 0.0001$, 99% CI: -0.378– -0.299). We do not observe significant variation of estimates across predominately Democrat or Republican voting states and counties, and our results are robust to alternative specifications of bandwidth, fixed effects, and data cleaning decisions.

Keywords: *mental health, controlled interrupted time series, Google searches, United States, COVID-19 vaccines.*

3.1 Introduction

It has been well-documented that throughout the pandemic, symptoms of depression and anxiety have markedly increased among US adults. While it is likely that the pandemic has a direct effect on worsened mental health status due to fear of contracting and spreading the virus, public health responses to the pandemic—including lockdowns, school closures, and social distancing measures—likely have an indirect effect as well. Existing research suggests that the effects of these measures on mental health vary, and may be protective, null, or even harmful. Studies of lockdowns in multiple countries, for example, point to worsened feelings of isolation and hopelessness exacerbated by isolation measures. By contrast, the distribution of safe and effective vaccines against COVID-19 has been shown to reduce symptoms of depression and anxiety by as much as XXX.

- Describe symptoms database and reference published literature using it to predict COVID-19 cases and deaths^{80–82}

A recently published evaluation of Google's COVID-19 Search Trends Symptoms Dataset found strong correlation between search trends for depression and anxiety with indicators of mental health service utilization and need reported in the US Census Household Pulse Survey (HPS) with rates of emergency department visits for mental health condition as reported in the US Centers for Disease Control and Prevention's (CDC) National Syndromic Surveillance Program (NSSP).¹

controlled interrupted time series (CITS) interrupted time series (ITS)

- Motivation to explore vaccine announcement: evidence that vaccination itself reduced depression and anxiety – do we see earlier reductions from an anticipatory effect?
- Motivation to analyze by polity: Vaccination became politically charged in the US, possible bias from impact of 2020 election on mental health searches

- Overview of approach: CITS using searches for headache as a control, adjusting for fixed effects, subgroup analysis by polity, analysis for 6 different mental health symptoms

3.2 Methods

3.2.1 Data

3.2.1.1 Shock date We take as our first credible signal of the imminent availability of multiple safe and effective COVID-19 vaccines to be November 16, 2020. On November 9, Pfizer announced than early vaccine trial data showed 90% efficacy;⁸³ on the 16th, Moderna similarly announced preliminary results showing 94.5% efficacy for their vaccine.⁸⁴ While U.S. Food and Drug Administration (FDA) Emergency Use Authorization (EUA) was not granted until December, the concurrent announcements of vaccine efficacy were widely reported and interpreted by many public health practitioners, policymakers, and the general public as a substantial signal of a new phase of the pandemic, with Moderna’s chief executive officer calling the news “a game changer” in the fight against COVID-19.

3.2.1.2 Symptoms dataset We accessed aggregated national and subnational data from Google’s COVID-19 Search Trends Symptoms Dataset⁸⁵ (hereafter referred to as the symptoms dataset) between January 1, 2020 and April 1, 2021. The symptoms dataset provides time series data of search term density, standardized to pairs of health symptoms and regions (e.g., searches for depression in Australia or for fever in Cook County, Illinois) and normalized within each pair based on the symptom’s relative popularity. The time series of search density for each symptom-region pair also contains artificial noise, as Google’s differential privacy technique to data aggregation and anonymization adds random noise to protect user privacy (the errors are symmetrically distributed).

Search density data for over 400 symptoms are reported across national and subnational regions

of six countries: Australia, the United Kingdom, Ireland, New Zealand, Singapore, and the United States. In the United States, subnational regions include states and counties. Because the aggregated search density trends were constructed based on relative search population within each region, comparison of search density for a specific symptom between different regions is not meaningful; however, comparing search density within regions (or a group of regions) is feasible both over time and across different symptoms.

For our analysis, we utilized three levels of region from the symptoms dataset: 1) national level data from the six countries in the dataset; 2) U.S. state level data across 51 states; and 3) U.S. county level data reported by 2,505 counties. (Though there are over 3,000 counties in the U.S., due to data privacy concerns, smaller county results were not included in the symptoms dataset.) Following the convention of the symptoms dataset, we will refer to the geographic units (e.g., states, counties, and nations) within the data as “regions.”

3.2.1.3 Voting dataset We further obtained county-level presidential election returns for 2020 from the MIT Election Data and Science Lab,⁸⁶ which we then used to calculate aggregate county and state votes (including absentee, early, and election day ballots) won by each candidate. The aggregate votes were then used to determine vote share and margins (e.g., the percentage points difference in vote share between the candidate with the most votes to the runner up). These margins were then used to sort counties and states into quintiles, such that the 20% most Republican-voting localities appearing in the symptoms dataset were sorted into the first quintile and the 20% most Democratic-voting localities sorted into the fifth).

3.2.1.4 Population data Population estimates for 2020 by Federal Information Processing Standards (FIPS) code were obtained from the United States Department of Agriculture (USDA) Economic Research Service.

3.2.2 Statistical analysis

All analyses were completed using R (version 4.2.1).³²

3.2.2.1 Modeling approach We use an ITS approach to model Google search density for a given symptom d using the following baseline equation:

$$Y_{d,g,i} = \lambda_0 + \lambda_1 time_t + \alpha_d Post_{d,i} + \beta_d time_t * post_{d,i} + \theta_r + T'_t \chi + \epsilon_{it} , \quad (3.1)$$

where $time_t$ is a continuous variable that captures the days leading to the vaccine announcement, $Post_i$ is an indicator variable which equals 1 in the period after the shock data and 0 otherwise, θ_r is a fixed effect for region r , and $T'_t \chi$ is a matrix of time-vary fixed effects (i.e., month and day of week).

In our model, α_d can be interpreted as a level or intercept associated with the shock date—that is, the immediate difference in search density for a disease d following November 19, 2020. The term β_d —i.e., the slope change—can be interpreted as the sustained change in search density in the days following November 16th.

We apply this model for all available 420 diseases with county-level data. As search density may rapidly change in response to a shock, we trimmed the bandwidth of dates to fit our model to forty days before and after November 16, 2020.

To control for time-varying confounders which may have affected symptom search trends during the study period, we applied a CITS approach to contrast how searches for mental health symptoms varied above and beyond changes in search density for a comparable physical complaint (i.e., headaches).

After reviewing the list of symptoms for which search density data were available, we identified the following 18 mental health related symptoms: anxiety, Asperger syndrome, attention deficit

hyperactivity disorder, binge eating, clouding of consciousness, compulsive behavior, depersonalization, depression, dysphoria, generalized anxiety disorder, impulsivity, major depressive disorder, manic disorder, mood disorder, panic attack, psychosis, self harm, and suicidal ideation.

For each of these mental health symptoms, d , we ran the following model to predict search density:

$$Y_{d,it} = \lambda_0 + \lambda_1 time_t + \lambda_2 Post_t + \lambda_3 time_t * Post_t + \alpha_d treated_{di} + \beta_d time_t * treated_{di} + \delta_d Post_i * treated_{di} + \gamma_d time_t * Post_i * treated_{di} + \theta_g + T_t' \chi + \epsilon_{it} , \quad (3.2)$$

where $treated_{di}$: is an indicator variable which equals 1 if the observation is for a mental health condition d , 0 if for headaches. The CITS effect estimates of interest are given by δ , which reflects the additional level shift among mental health related symptoms searches compared to searches for headaches after the vaccine announcement, and γ , the additional change in search density over time (i.e., slope change) comparing the same.

Given the high number of observations in our sample, we evaluated significance against an alpha of 0.01, and we constructed 99% confidence intervals using heteroskedasticity-robust standard errors.

3.2.2.1.1 Sensitivity analysis As with other quasi-experimental methods, it is recommended that the modeling choices and specifications of a CITS analysis be evaluated using a sensitivity analysis. To do so, we defined a list of seven methodological choices concerning data processing and modeling assumptions and interacted these choices to generate all their plausible combinations. These combinations were then conducted to allow for a multiverse analysis to identify how sensitive effect estimates and confidence intervals were to different methodological choices.

These criteria used to generate the plausible model combinations are outlined in Table 3.1.

Table 3.1: Alternative specifications, data processing, and modeling decisions for multiverse analysis.
*: preferred specification.

1. Data cleaning for outcome data
a) Linear interpolation to replace outliers *
b) No adjustment (raw data)
2. Region level
a) U.S. counties*
b) U.S. states
c) International ($n = 6$)
3. Bandwidth
a) ± 40 days
b) ± 50 days
c) ± 60 days
4. Day of week fixed effects
a) Included *
b) Excluded
5. Month fixed effects
a) Included *
b) Excluded
6. Regional fixed effects
a) Included *
b) Excluded

First, we considered the role of data cleaning in the outcome data, which involved outlier smoothing using Friedman's nonparametric super smoother regression estimator.⁶⁰ Second, we compared the level of region of aggregated data, using U.S. counties, U.S. states, and, finally, national trends from the six counties in the sample. Third, we evaluated sensitivity to our specification of the bandwidth cut-off around the shock date, extending this from ± 40 days to 40 and 60 days. Fourth, we toggled whether to account for day of week fixed effects. Fifth, we toggled month fixed effects. Sixth, we similarly toggled regional fixed effects (i.e., fixed effects for states in the U.S. state

level data, fixed effects for counties in the U.S. county level data, etc.).

Interacting these choices resulted in 144 plausible models for each symptom. Each of the 144 models were run for all 18 mental health related symptoms, resulting in 2,736 models being conducted overall.

3.2.2.1.2 Subgroup analysis Two subgroup analyses were conducted to investigate the generalizability of the findings of the main analysis and to explore potential heterogeneities in measures of association.

The first subgroup analysis applied the CITS approach against all 18 mental health related symptoms against search data from each of the six countries in the sample, using our nationally aggregated data. This analysis aimed to investigate the extent to which effects observed in US states and counties were also seen in other countries.

The second subgroup analysis applied the CITS approach to the 20% most Republican-voting localities (hereafter referred to as red states/counties) and to the 20% most Democratic-voting localities (hereafter referred to as blue states/counties) based on 2020 presidential election vote share. A growing body of evidence has documented that political ideology can play a role in how receptive people are to vaccination; this has been highlighted throughout the COVID-19 pandemic, with people identifying as conservative being more likely to express skepticism of public health authorities and the scientific community and being more likely to express concerns about the safety, effectiveness, or necessity of vaccines. Our subgroup analysis comparing CITS effect estimates in blue vs. red states aimed to investigate whether the initial response to imminent safe and effective COVID-19 vaccines showed evidence of heterogeneity by predominant political ideology, under the hypothesis that if conservative voters were more likely to be averse to vaccination, any impact on mental health related symptom search density from the announcement of upcoming vaccines would

be lesser in red states and counties compared to blue ones.

3.2.3 Ethics statement

The Institutional Review Board (IRB) of the Harvard T.H. Chan School of Public Health has determined that the study was not human subjects research, and that additional review was not required (protocol number: IRB23-0095, determined on January 25, 2023).

3.3 Results

The ITS estimates for the immediate (level shift) and sustained (slope change) effects associated with the announcement of vaccine safety and efficacy data on search density for all 420 are presented in Figure 14.

For most symptoms, search density exhibited negligible differences following the announcement, with small positive level shifts offset by modest negative slope changes. For four mental health symptoms, however, we observed relatively large, negative slope changes for searches for anxiety (-0.078, $p < 0.0001$, 99% CI: -0.082 – -0.073), depression (-0.059, $p < 0.0001$, 99% CI: -0.062 – -0.056), major depressive disorder (MDD)(-0.053, $p < 0.0001$, 99% CI: -0.056 – -0.05), and attention deficit hyperactivity disorder (ADHD)(-0.046, $p < 0.0001$, 99% CI: -0.048 – -0.043). With respect to level shifts, changes for anxiety (0.035, $p = 0.08$, 99% CI: -0.016 – 0.086) and depression (0.107, $p < 0.0001$, 99% CI: 0.071 – 0.143) were close to zero, while those for MDD (0.23, $p < 0.0001$, 99% CI: 0.197 – 0.264) and ADHD (0.235, $p < 0.0001$, 99% CI: 0.202 – 0.268) were approximately 0.3 percentage points.

While our ITS analysis provided suggestive evidence that search density for mental health symptoms might have changed in the post-announcement period, it also highlighted that searches may have generally changed across other diseases at the same time. Our CITS estimates of each

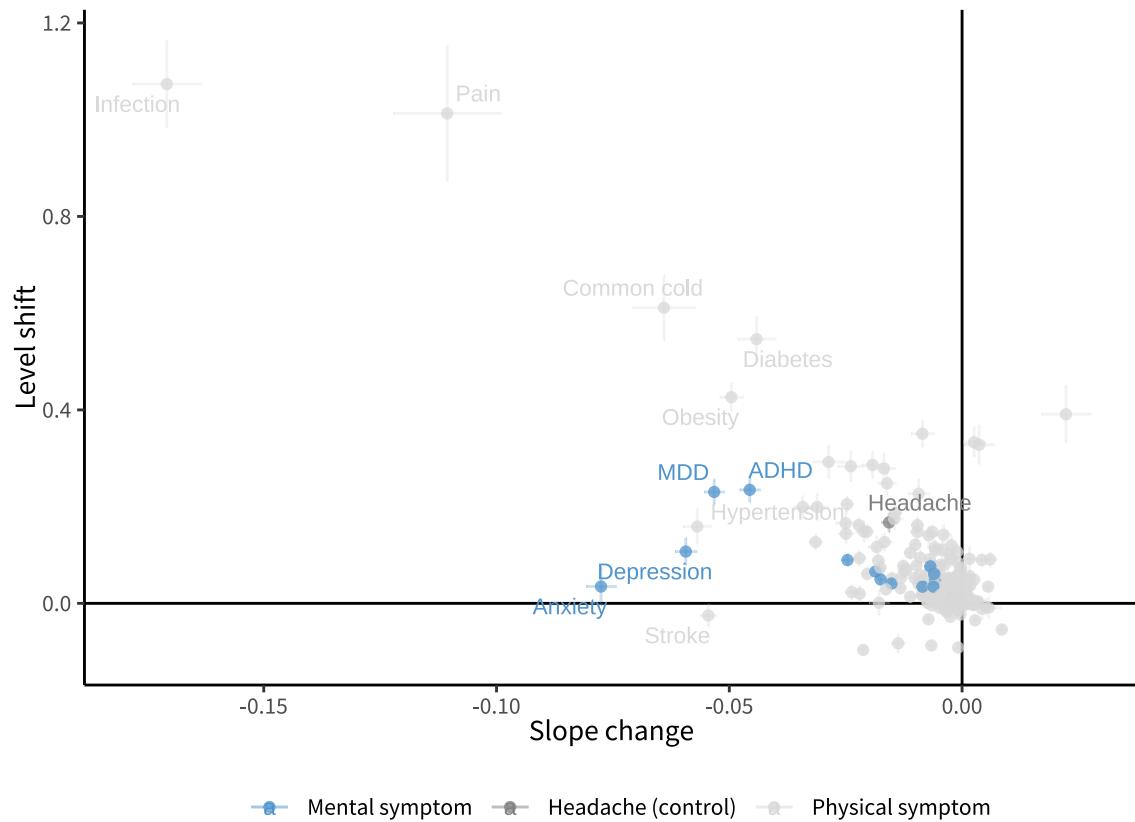


Figure 14: Interrupted time series (ITS) effect estimates and confidence intervals by symptom. Effect estimates are presented by points; for each symptom, the estimated slope change per day is shown on the x-axis, while the level shift over the post-announcement period is shown on the y-axis. The horizontal and vertical bars next to each point represent the 99% confidence intervals for the estimate slope change and level shift, respectively. Mental health-related symptoms are shown in blue, while physical symptoms are shown in grey. ADHD: Attention deficit hyperactivity disorder. MDD: Major depressive disorder.

mental health symptom (Figure 15) using searches for headaches as a comparison broadly echoed our ITS analysis, with most conditions showing level and slope changes close to the null. For three conditions, our CITS analysis showed relatively large slope changes with searches for anxiety (-0.035, $p < 0.0001$, 99% CI: -0.037 – -0.032), depression (-0.029, $p < 0.0001$, 99% CI: -0.031 – -0.027), and MDD (-0.012, $p < 0.0001$, 99% CI: -0.013 – -0.01) all showing sustained declines. All three of these symptoms had relatively large slope changes in our ITS analysis. In addition, the CITS level shift (i.e., the relative immediate effect) for anxiety was -0.035 percentage points ($p < 0.0001$, 99% CI: -0.037 – -0.032), a decrease double in magnitude compared to the majority of estimates for other symptoms.

In both our analyses, search trends for anxiety, depression, and MDD showed potential immediate and sustained declines in density following November 16th. Search density for these three symptoms and the comparison search data for headaches is plotted in Figures 16 through 18 at the level of U.S. states, U.S. counties, and international data. We observed relatively strong concordance between our CITS estimates and the observed trends in the data, with strong fit to both mental health symptoms and headaches. We further observed strong within-week patterns in searches, supporting our inclusion of fixed effects to account for this weekly periodicity.

Our multiverse analysis further underscored the robustness of our findings concerning the relatively large negative immediate and sustained effects on searches for anxiety and depression, in particular (Figure 19). For anxiety, all 144 models had negative level shifts and slope changes. For depression, all 144 models had negative slope changes, of which only 24 models had any positive level shift. For MDD, we similarly observed a universally negative slope change in all 144 models; however, the majority of models showed a positive level shift (96 models), whereas only 48 showed a downward level shift.

Examining the plausible model combinations of the multiverse analysis for these three symptoms

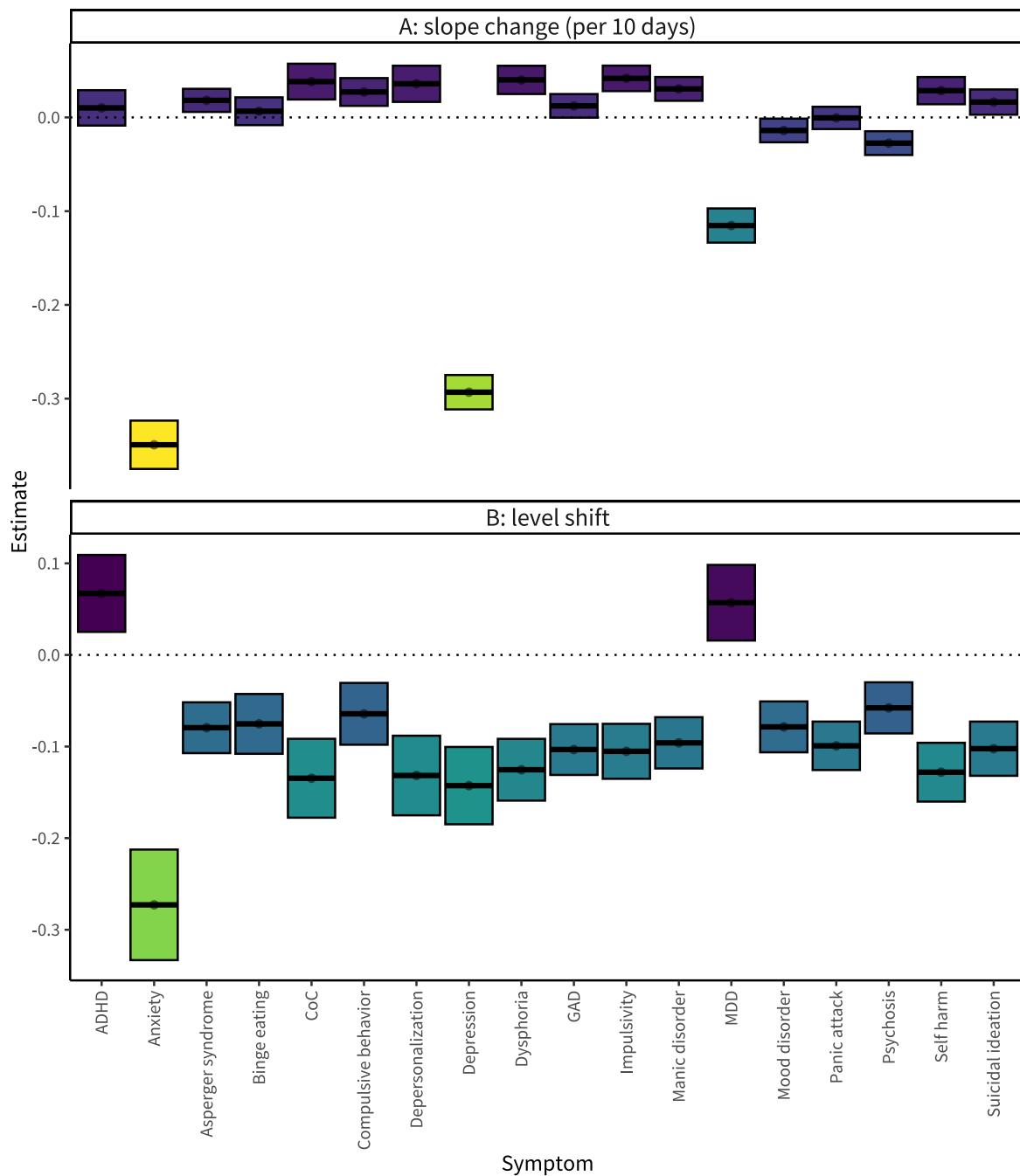


Figure 15: Controlled interrupted time series effect estimates (A: slope change per 10 days and B: level shift) on Google Search density by symptom. Effect estimates are represented as thick, horizontal lines in between colored bands, which represent the 99% confidence intervals for the estimates. Colors reflect the sign and magnitude of effect estimates. Dark blue values above zero indicate an increase in search density, while the yellow and green negative values indicate a decrease. The dotted horizontal line depicts a null effect. ADHD: Attention deficit hyperactivity disorder. CoC: clouding of consciousness. GAD: Generalized anxiety disorder. MDD: Major depressive disorder.

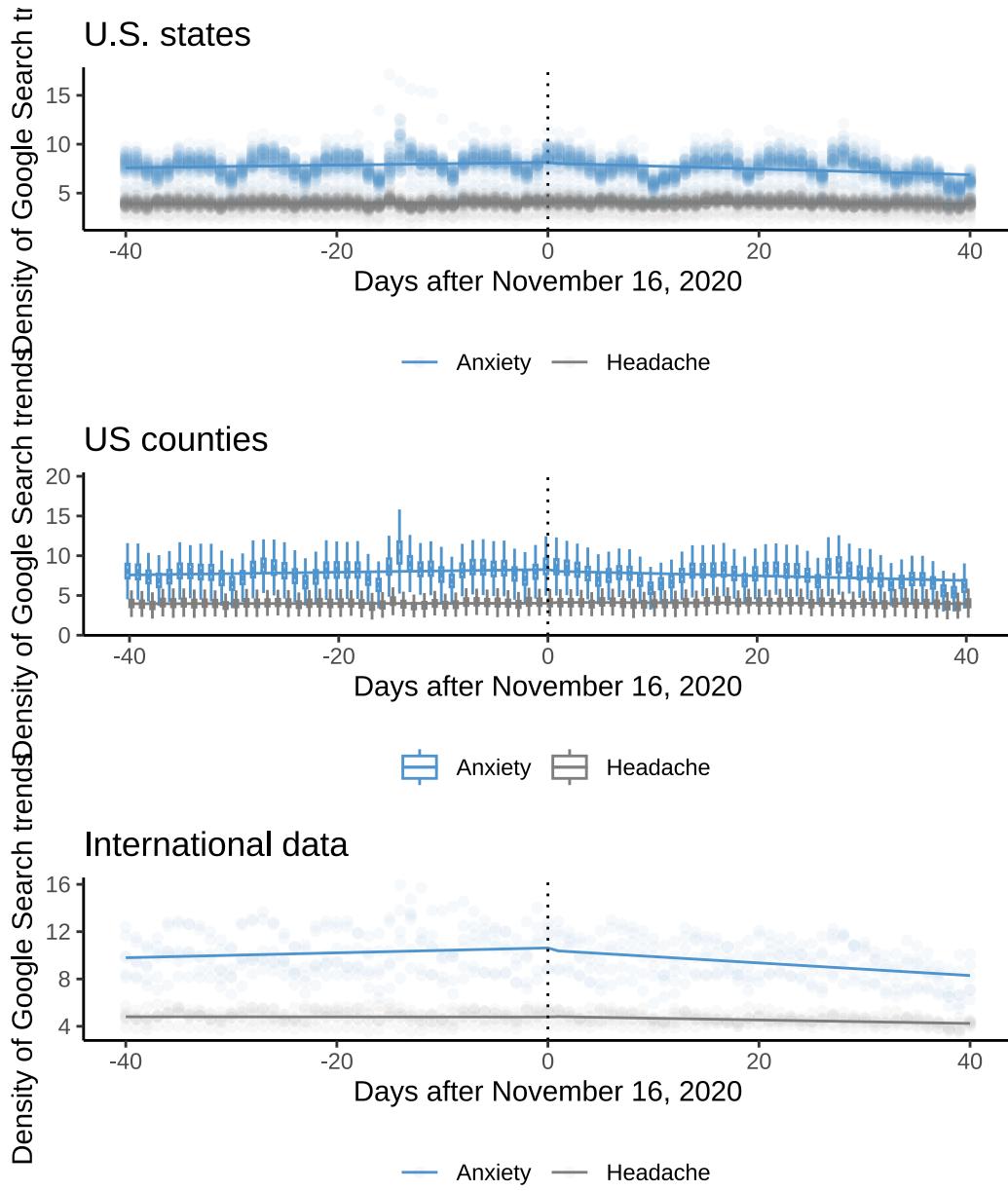


Figure 16: Density of Google Search trends for anxiety, by region and as a function of time. In each row, search density data for two symptoms are displayed: anxiety in blue and headaches in grey. In the first column, data from US states are shown, where each point represents the search density of a specific symptom on a specific date in a specific state. In the second column, data from US counties are shown; because of the large number of counties reporting data, county-level search data are shown as daily boxplots. In the third column, national data from Australia, the United Kingdom, Ireland, New Zealand, Singapore, and the United States are shown. Each graph shows the density of symptom searches on the y-axis, while time is centered and displayed as days prior to and following November 16, 2020 on the x-axis. The solid lines show predicted lines of best fit under a basic controlled interrupted time series (CITS) model (i.e., no fixed effects). US: United States.

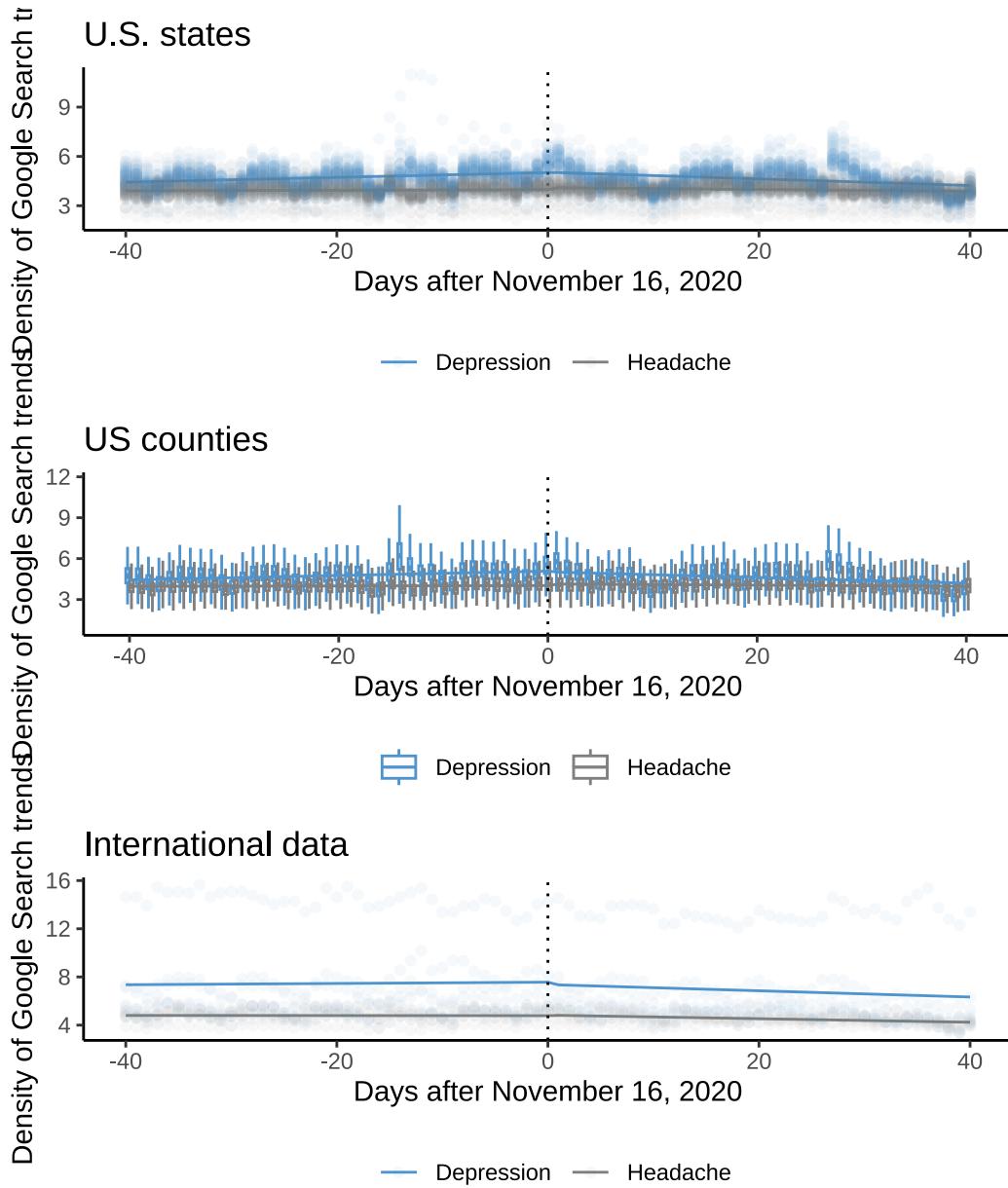


Figure 17: Density of Google Search trends for depression, by region and as a function of time. In each row, search density data for two symptoms are displayed: depression in blue and headaches in grey. In the first column, data from US states are shown, where each point represents the search density of a specific symptom on a specific date in a specific state. In the second column, data from US counties are shown; because of the large number of counties reporting data, county-level search data are shown as daily boxplots. In the third column, national data from Australia, the United Kingdom, Ireland, New Zealand, Singapore, and the United States are shown. Each graph shows the density of symptom searches on the y-axis, while time is centered and displayed as days prior to and following November 16, 2020 on the x-axis. The solid lines show predicted lines of best fit under a basic controlled interrupted time series (CITS) model (i.e., no fixed effects). US: United States.

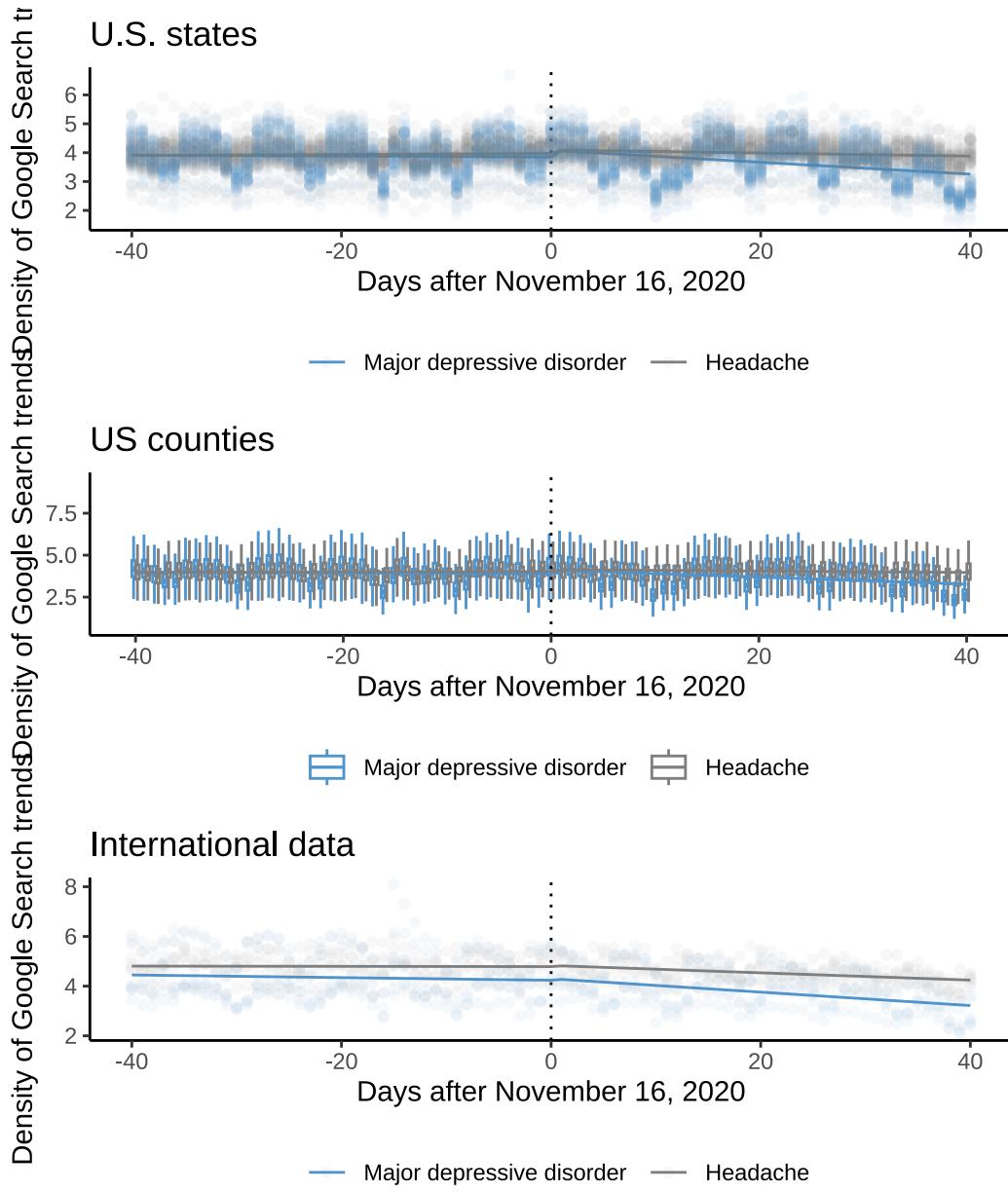


Figure 18: Density of Google Search trends for MDD, by region and as a function of time. In each row, search density data for two symptoms are displayed: MDD in blue and headaches in grey. In the first column, data from US states are shown, where each point represents the search density of a specific symptom on a specific date in a specific state. In the second column, data from US counties are shown; because of the large number of counties reporting data, county-level search data are shown as daily boxplots. In the third column, national data from Australia, the United Kingdom, Ireland, New Zealand, Singapore, and the United States are shown. Each graph shows the density of symptom searches on the y-axis, while time is centered and displayed as days prior to and following November 16, 2020 on the x-axis. The solid lines show predicted lines of best fit under a basic controlled interrupted time series (CITS) model (i.e., no fixed effects). US: United States.

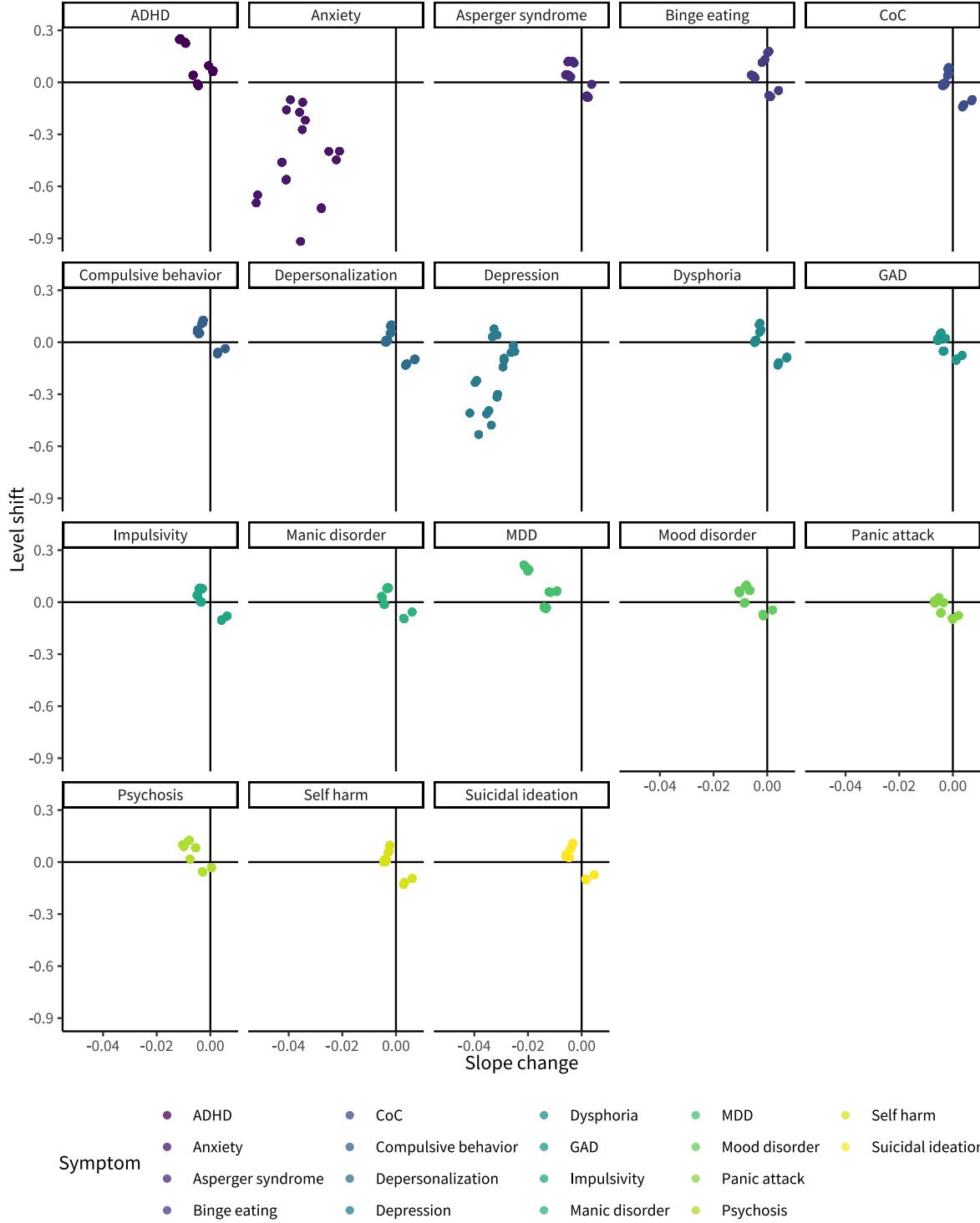


Figure 19: Controlled interrupted time series effect estimates by mental health related symptom for each model specification combination in multiverse analysis. Each point presents the effect estimates of a single model; for each symptom, the estimated slope change per day is shown on the x-axis, while the level shift over the post-announcement period is shown on the y-axis. ADHD: Attention deficit hyperactivity disorder. CoC: clouding of consciousness. GAD: generalized anxiety disorder. MDD: Major depressive disorder.

underscored the importance of regional level to inference, as the use of county-level data (with a greater number of observations) consistently showed similar effect estimates to state level estimates for each CITS estimand, but with much tighter confidence intervals, even when geographic fixed effects and narrower bandwidths were included. Slope changes and level shifts for anxiety, depression, and MDD are reported for each combination (144 models) in Figure 20. Across all models, the sustained change in search density for anxiety and depression is negative and significant at alpha of 0.01. In terms of the estimated level shifts, 90 models for anxiety (62%) had a statistically significant negative change, compared to 0 models with a positive one. For depression, of the 64 models with a statistically significant level shift estimate, all 64 models returned a negative level shift coefficient.

Turning to our subgroup analysis, we found modest evidence of effect estimates of similar magnitude comparing across nations (Figure 21). Across the most populous countries (Australia, the United Kingdom, and the United States), effect estimates were broadly consistent, with wider confidence intervals than our ITS or CITS main analysis results due to the smaller number of observations. Negative level shifts and slope changes were more pronounced in New Zealand compared to other nations; we caution, however, that owing to the construction of the Google search density data being relative to regions, this may be due to differences in search volume intensity for depression in New Zealand compared to other nations, and not due to a strong effect itself.

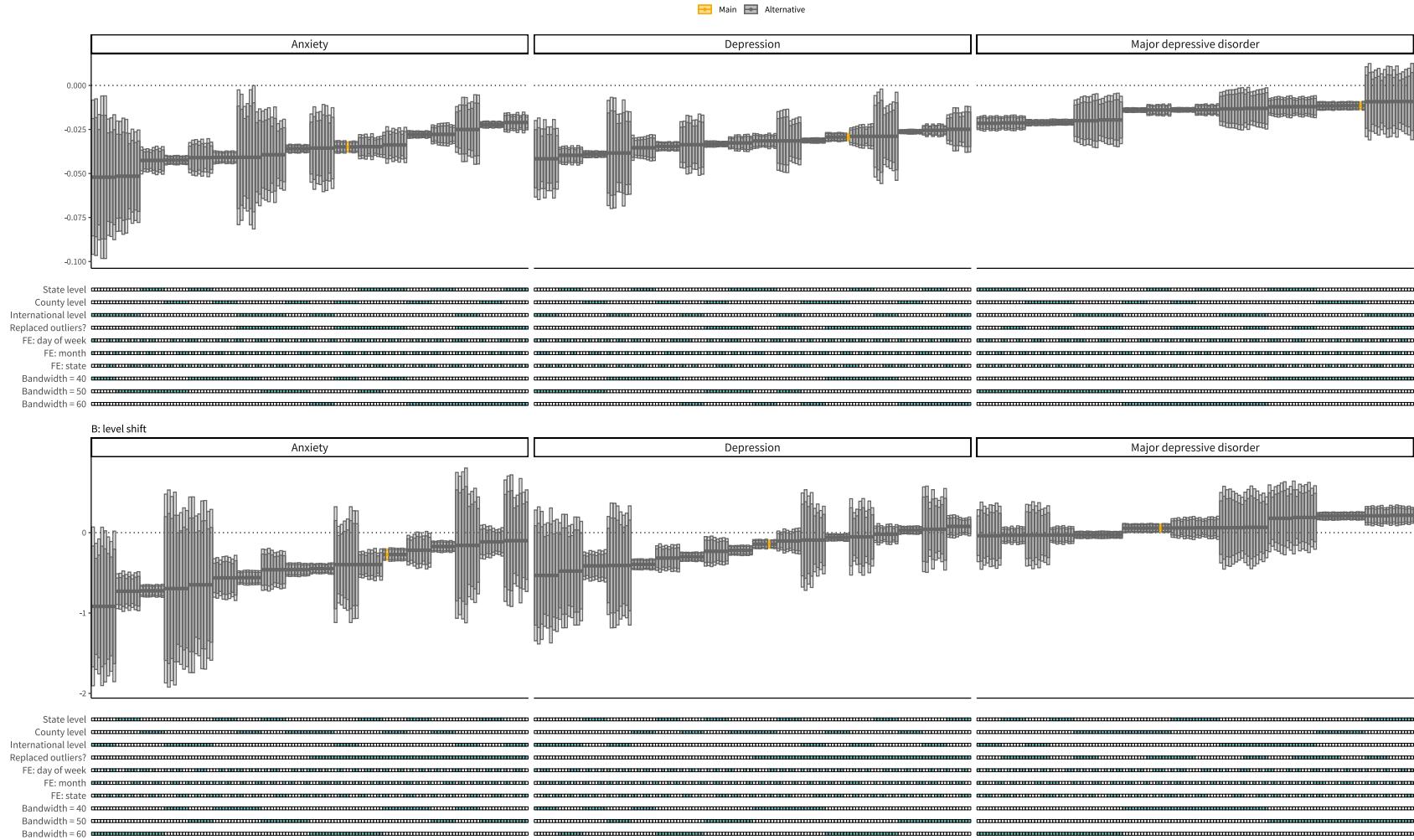


Figure 20: Specification curve depicting the CITS effect estimates and confidence intervals for search density, with panel A depicting the estimated slope change and panel B depicting the estimate level shift. Within each panel, the effect estimates across different models are depicted as circles in the upper graph; the darkly and lightly shaded regions above and below these circles correspond to 95% and 99% confidence intervals of these estimates, respectively. The dotted horizontal line depicts a null effect. The effect estimates and confidence intervals of the main specification are highlighted in orange. Below each model, a legend of shaded and unshaded boxes indicates which modeling decisions correspond to a given model, with boxes shaded teal showing active features. The three vertical columns show effect estimates by symptom. From left to right, these are anxiety, depression, and major depressive disorder. FE: fixed effects. CITS: controlled interrupted time series. FE: fixed effects. CITS: controlled interrupted time series.

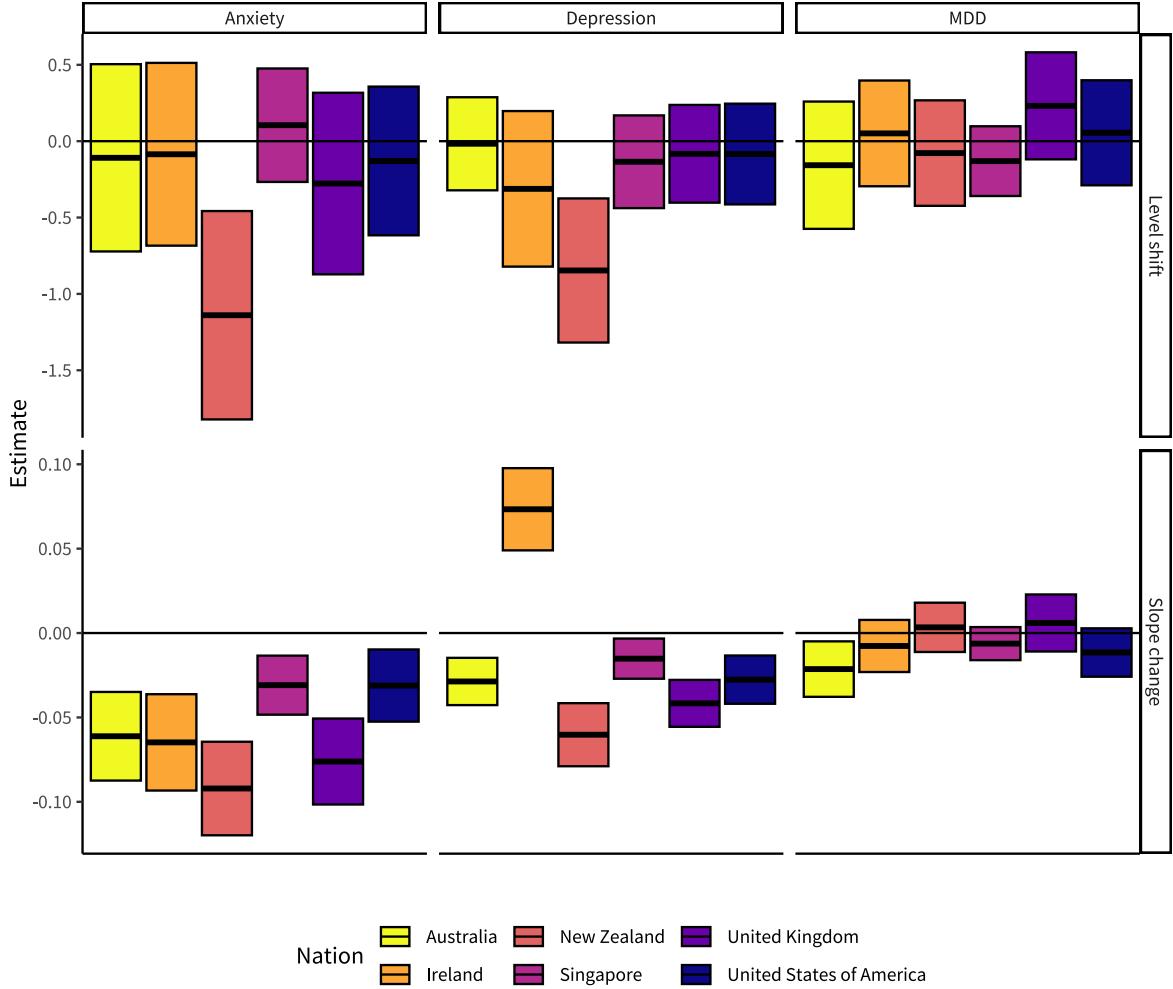


Figure 21: Controlled interrupted time series effect estimates by mental health related symptom for each model specification combination in multiverse analysis. Each point presents the effect estimates of a single model; for each symptom, the estimated slope change per day is shown on the x-axis, while the level shift over the post-announcement period is shown on the y-axis. ADHD: Attention deficit hyperactivity disorder. CoC: clouding of consciousness. GAD: generalized anxiety disorder. MDD: Major depressive disorder.

Results from our analysis comparing red and blue states and counties showed broad consistency in both slope changes and level shifts for searches for anxiety, depression, and MDD as found in our main analysis (Figure 22). This was particularly observed in our analysis of U.S. state-level data, where confidence intervals for the CITS effect estimates were statistically equivalent across red and blue states. In our county-level analysis, however, we observed larger immediate and

sustained declines in searches for depression among red counties than blue ones, with minor overlap in confidence intervals. The observed slope change for searches related to depression among red counties was -0.033 percentage points per day ($p < 0.0001$, 99% CI: -0.036 – -0.03), compared to -0.025 percentage points per day ($p < 0.0001$, 99% CI: -0.03 – -0.021) for blue counties. Similarly, a more pronounced level shift was observed in red counties than blue ones, -0.225 percentage points ($p < 0.0001$, 99% CI: -0.289 – -0.161) vs. -0.105 percentage points ($p = 0.008$, 99% CI: -0.208 – -0.003), respectively.

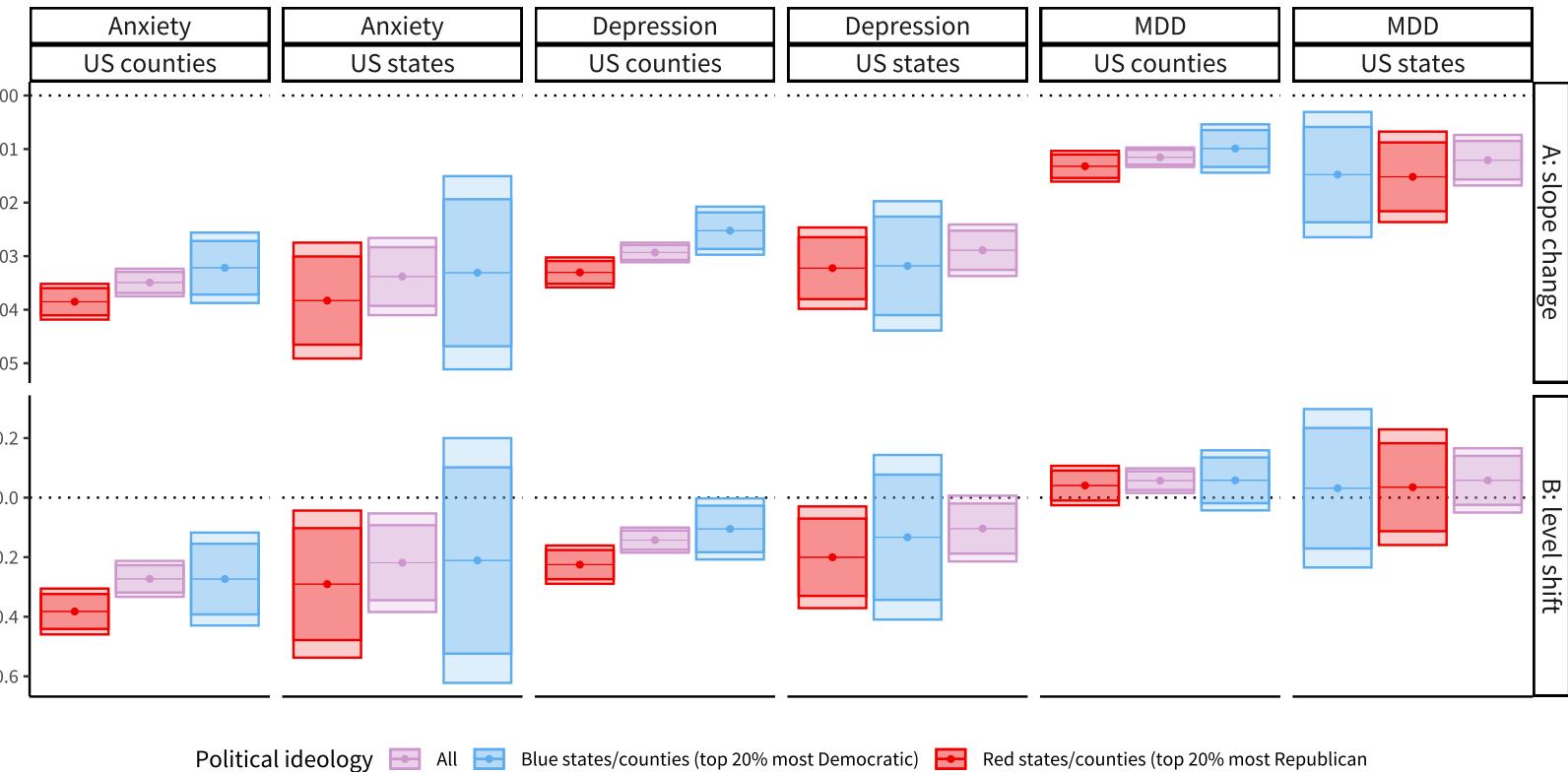


Figure 22: CITS effect estimates and confidence intervals symptom, region, and predominant political ideology, with panel A depicting the estimated slope change and panel B depicting the estimate level shift. The vertical panels show CITS effect estimates by three mental health symptoms (from left to right: anxiety, depression, and major depressive disorder); for each symptom, estimates are separately reported using county- and state-level data. For a given symptom and region, three CITS estimates are reported: one estimated from a sample of all counties or states (shown in purple), one conducted solely among the most Democratic counties or states (by 2020 presidential election vote share, shown in blue, and one among the most Republican counties or states (shown in red). Within each panel, the effect estimates across different models are depicted as points on a horizontal bar; the darkly and lightly shaded regions above and below these circles correspond to 95% and 99% confidence intervals of these estimates, respectively. The dotted horizontal line in each panel depicts a null effect. CITS: controlled interrupted time series. US: United States.

3.4 Discussion

- Shows that event the announcement of a safe and effective vaccine led to a significant shift in searches. If searches are taken as a reasonable proxy of mental health status, the period following the announcement saw both a sharp decline in depression and anxiety
- Lack of heterogeneity by polity is interesting, given evidence that polity is a strong predictor of attitudes towards COVID-19 vaccination. Also makes bias from an uncommon shock (e.g., 2020 election) less likely to explain the results

Conclusion

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Supplementary materials

Appendix 1

Table S1.1: The global economic burden of mental disorders, by year and approach, calculated by Bloom and colleagues and adjusted to 2019 USD using gross domestic product deflator adjustment. Estimates are in trillions. DALY: disability-adjusted life year. GDP: gross domestic product. VSL: value of a statistical life.

Year	Cost of illness (COI)			Value of lost output (VLO) 19.09*	Value of losses using VSL approach †
	Direct costs	Indirect costs	Total		
2010	0.96	1.96	2.92		1.57 4.72
2030	2.34	4.74	7.08		2.92 8.75
Average	1.50	3.05	4.55		2.14 6.42

* Annual VLO estimates are not reported by disease category. The estimate of VLO is the total for the range 2010-2030 for mental disorders.

† Authors' calculations based on Bloom and colleagues.

Table S1.2 The economic value of mental disorder losses, using VSL approach, by year and monetary value assigned to one DALY. Authors' calculations based on Bloom and colleagues and adjusted to 2019 USD using gross domestic product deflator adjustment. Estimates are in trillions.

World Bank income group	1 DALY=		1 DALY=	
	1x GDP per capita		3x GDP per capita	
	2010	2030	2010	2030
High-income	1.02	1.32	3.05	3.97
Upper-middle-income	0.35	1.18	1.05	3.53
Lower-middle-income	0.17	0.36	0.50	1.09
Low-income	0.04	0.07	0.11	0.22
Global	1.57	2.92	4.72	8.75

DALY: disability-adjusted life year. VSL: value of a statistical life. GDP: gross domestic product.

Table S1.3: Hierarchical classification of mental disorders in the Global Burden of Disease (GBD) 2019 study.

Level 1	Level 2	Level 3	Level 4
Non-communicable diseases			
	Mental disorders		
		Schizophrenia	
		Depressive disorders	Major depressive disorder Dysthymia
		Bipolar disorder	
		Anxiety disorders	
		Eating disorders	Anorexia nervosa Bulimia nervosa
		Autism spectrum disorders	
		Attention-deficit/hyperactivity disorder	
		Conduct disorder	
		Idiopathic developmental intellectual disability	
		Other mental disorders	
Not classified as “mental disorders” under GBD 2019			
	Substance use disorders		
		Alcohol use disorders	Opioid use disorders Cocaine use disorders Amphetamine use disorders
		Drug use disorders	Cannabis use disorders Other drug use disorders
	Neurological disorders		
		Alzheimer's disease and other dementias	
		Parkinson's disease	
		Idiopathic epilepsy	
		Multiple sclerosis	
		Motor neuron disease	
		Headache disorders	Migraine Tension-type headache
		Other neurological disorders	
Musculoskeletal disorders			
Injuries			
	Self-harm and interpersonal violence		
		Self-harm	Self-harm by firearm Self-harm by other specified means

Table S1.4: Years lived with disability (YLDs) attributable to mental disorders as totals (millions) and percentages of overall burden, by World Bank income group classification and GBD region, under three estimation approaches.

	Original approach						Reallocation approach						Composite approach					
	YLDs			% of burden			YLDs			% of burden			YLDs			% of burden		
	Estimate	Lower bound	Upper bound	Estimate	Lower bound	Upper bound	Estimate	Lower bound	Upper bound	Estimate	Lower bound	Upper bound	Estimate	Lower bound	Upper bound	Estimate	Lower bound	Upper bound
Global	125.3	93.0	163.2	14.6	14.5	14.7	247.2	140.2	401.0	28.7	21.9	36.2	247.2	140.2	401.0	28.7	21.9	36.2
High income	24.5	18.1	32.0	14.1	14.0	14.3	53.9	30.7	87.5	31.1	23.7	39.2	53.9	30.7	87.5	31.1	23.7	39.2
Upper-middle income	45.6	33.8	59.7	14.5	14.4	14.6	92.8	51.9	152.6	29.5	22.1	37.4	92.8	51.9	152.6	29.5	22.1	37.4
Lower-middle income	44.9	33.0	58.9	14.5	14.3	14.6	83.5	45.6	138.7	26.9	19.8	34.4	83.5	45.6	138.7	26.9	19.8	34.4
Low income	10.1	7.4	13.5	16.5	16.3	16.7	16.8	9.4	27.5	27.3	20.8	34.1	16.8	9.4	27.5	27.3	20.8	34.1
East Asia	21.0	15.7	27.3	13.2	13.1	13.2	44.1	24.8	72.2	27.7	20.8	35.0	44.1	24.8	72.2	27.7	20.8	35.0
Southeast Asia	9.1	6.7	11.9	13.4	13.5	13.6	19.5	9.9	34.2	28.9	19.9	39.0	19.5	9.9	34.2	28.9	19.9	39.0
Oceania	0.2	0.1	0.2	13.6	13.6	13.7	0.3	0.2	0.5	26.0	18.6	34.0	0.3	0.2	0.5	26.0	18.6	34.0
Central Asia	1.3	0.9	1.7	14.2	14.2	14.4	2.7	1.5	4.5	30.2	22.4	38.7	2.7	1.5	4.5	30.2	22.4	38.7
Eastern Europe	3.5	2.6	4.5	12.7	12.7	12.9	8.0	4.7	12.9	29.4	23.2	36.6	8.0	4.7	12.9	29.4	23.2	36.6
Central Europe	1.7	1.3	2.3	11.6	11.5	11.7	4.0	2.3	6.6	26.8	20.2	34.2	4.0	2.3	6.6	26.8	20.2	34.2
Caribbean	0.8	0.6	1.0	16.7	16.4	16.9	1.4	0.8	2.2	29.2	22.2	36.6	1.4	0.8	2.2	29.2	22.2	36.6
Central Latin America	4.1	3.0	5.4	15.8	15.5	16.0	8.0	4.4	13.2	30.6	22.8	38.9	8.0	4.4	13.2	30.6	22.8	38.9
Tropical Latin America	5.1	3.7	6.6	18.8	18.7	19.0	9.6	5.5	15.5	35.6	27.4	44.6	9.6	5.5	15.5	35.6	27.4	44.6
Andean Latin America	1.1	0.8	1.4	17.5	17.1	17.9	1.9	1.1	3.1	30.6	23.6	38.0	1.9	1.1	3.1	30.6	23.6	38.0
North Africa and Middle East	10.7	7.8	14.1	19.4	19.2	19.8	18.7	10.4	30.7	34.0	25.6	43.0	18.7	10.4	30.7	34.0	25.6	43.0
Southern Sub-Saharan Africa	1.2	0.9	1.6	14.1	13.9	14.5	2.4	1.4	3.8	27.1	20.9	33.6	2.4	1.4	3.8	27.1	20.9	33.6
Western Sub-Saharan Africa	6.7	4.9	9.0	14.5	14.4	14.7	12.2	6.5	20.7	26.3	19.0	34.0	12.2	6.5	20.7	26.3	19.0	34.0
Central Sub-Saharan Africa	2.1	1.5	2.8	16.8	16.5	17.1	3.4	1.9	5.6	27.4	20.7	34.3	3.4	1.9	5.6	27.4	20.7	34.3
Eastern Sub-Saharan Africa	5.8	4.2	7.7	16.5	16.2	16.8	9.4	5.5	15.0	26.6	21.1	32.5	9.4	5.5	15.0	26.6	21.1	32.5
South Asia	28.8	21.2	37.6	14.1	14.0	14.2	52.7	29.1	86.8	25.9	19.1	32.8	52.7	29.1	86.8	25.9	19.1	32.8
Southern Latin America	1.3	0.9	1.6	16.5	16.3	16.7	2.4	1.4	3.8	31.2	24.3	38.6	2.4	1.4	3.8	31.2	24.3	38.6
Western Europe	9.4	7.0	12.4	15.4	15.3	15.6	19.4	10.9	31.9	31.7	24.0	40.4	19.4	10.9	31.9	31.7	24.0	40.4
High-income North America	8.0	6.0	10.4	13.7	13.6	13.9	19.2	11.2	30.5	33.0	25.6	41.0	19.2	11.2	30.5	33.0	25.6	41.0
Australasia	0.7	0.5	0.9	17.7	17.5	18.0	1.3	0.8	2.0	32.6	26.2	39.3	1.3	0.8	2.0	32.6	26.2	39.3
High-income Asia Pacific	2.7	2.0	3.5	10.9	10.8	11.0	6.4	3.6	10.5	25.8	19.6	33.0	6.4	3.6	10.5	25.8	19.6	33.0

Table S1.5: Years of life lost (YLLs) attributable to mental disorders as totals (millions) and percentages of overall burden, by World Bank income group classification and GBD region, under three estimation approaches.

	Original approach						Reallocation approach						Composite approach					
	YLLs			% of burden			YLLs			% of burden			YLLs			% of burden		
	Estimate	Lower bound	Upper bound	Estimate	Lower bound	Upper bound	Estimate	Lower bound	Upper bound	Estimate	Lower bound	Upper bound	Estimate	Lower bound	Upper bound	Estimate	Lower bound	Upper bound
Global	-	-	-	-	-	-	74.0	55.0	108.6	4.4	3.5	6.0	170.5	136.5	207.3	10.2	8.7	11.4
High income	-	-	-	-	-	-	20.4	14.3	31.9	10.6	7.7	15.7	27.1	22.0	32.8	14.0	11.9	16.1
Upper-middle income	-	-	-	-	-	-	24.7	15.9	41.5	4.9	3.6	7.2	63.8	47.4	83.5	12.7	10.8	14.5
Lower-middle income	-	-	-	-	-	-	25.3	17.8	37.1	3.4	2.8	4.4	63.9	44.6	86.9	8.7	6.9	10.2
Low income	-	-	-	-	-	-	3.5	2.2	5.6	1.5	1.1	1.9	15.5	10.4	22.5	6.5	5.2	7.8
East Asia	-	-	-	-	-	-	11.7	7.0	20.9	4.9	3.4	7.7	28.5	20.8	37.6	12.0	10.1	13.8
Southeast Asia	-	-	-	-	-	-	3.8	2.2	6.5	2.9	2.0	4.3	12.8	8.8	17.8	9.8	8.0	11.7
Oceania	-	-	-	-	-	-	0.1	0.0	0.1	1.7	1.2	2.2	0.3	0.2	0.5	8.2	6.6	9.9
Central Asia	-	-	-	-	-	-	1.1	0.8	1.5	5.4	4.6	6.4	2.0	1.5	2.7	10.2	8.6	11.9
Eastern Europe	-	-	-	-	-	-	5.4	4.0	7.8	8.8	7.4	11.1	8.1	6.0	10.6	13.1	11.0	15.1
Central Europe	-	-	-	-	-	-	1.7	1.1	2.9	6.7	5.0	9.6	2.8	1.9	3.9	10.9	9.2	12.7
Caribbean	-	-	-	-	-	-	0.4	0.2	0.6	3.8	2.8	5.2	1.3	0.9	1.9	13.0	10.8	15.2
Central Latin America	-	-	-	-	-	-	2.1	1.3	3.4	5.1	4.0	6.9	6.2	4.4	8.6	15.3	13.1	17.6
Tropical Latin America	-	-	-	-	-	-	2.0	1.4	3.2	5.0	3.7	7.6	7.4	6.2	8.6	18.3	16.1	20.5
Andean Latin America	-	-	-	-	-	-	0.4	0.2	0.7	4.6	3.2	6.3	1.3	0.8	1.9	13.6	11.4	16.0
North Africa and Middle East	-	-	-	-	-	-	2.8	1.7	4.9	3.5	2.5	5.2	12.6	8.9	17.4	15.9	13.5	18.4
Southern Sub-Saharan Africa	-	-	-	-	-	-	0.8	0.6	1.2	2.8	2.2	3.6	2.3	1.7	3.1	7.9	6.5	9.3
Western Sub-Saharan Africa	-	-	-	-	-	-	2.5	1.5	4.1	1.1	0.8	1.6	8.6	5.4	12.8	4.0	3.0	5.0
Central Sub-Saharan Africa	-	-	-	-	-	-	0.7	0.5	1.1	1.6	1.2	2.0	2.9	1.9	4.3	6.5	5.0	8.0
Eastern Sub-Saharan Africa	-	-	-	-	-	-	1.9	1.3	3.0	1.5	1.2	1.9	6.4	4.4	9.2	4.9	3.9	5.9
South Asia	-	-	-	-	-	-	18.0	13.3	25.3	4.2	3.5	5.3	43.3	30.8	57.4	10.1	8.1	12.0
Southern Latin America	-	-	-	-	-	-	0.7	0.5	1.0	6.5	5.0	9.5	1.5	1.2	1.7	13.8	11.9	15.6
Western Europe	-	-	-	-	-	-	6.1	4.0	10.4	9.4	6.1	15.6	9.1	7.5	10.7	13.8	11.7	16.0
High-income North America	-	-	-	-	-	-	7.9	6.5	10.6	12.6	10.5	16.8	9.8	8.3	11.2	15.5	13.3	17.7
Australasia	-	-	-	-	-	-	0.4	0.3	0.6	11.7	8.5	17.7	0.6	0.5	0.7	16.8	14.4	19.2
High-income Asia Pacific	-	-	-	-	-	-	3.4	1.9	6.0	13.5	7.7	23.2	2.7	2.2	3.2	10.6	8.7	12.5

Table S1.6: Deaths attributable to mental disorders as totals (millions) and percentages of overall burden, by World Bank income classification and GBD region, under three estimation approaches

	Original approach						Reallocation approach						Composite approach					
	Deaths			% of burden			Deaths			% of burden			Deaths			% of burden		
	Estimate	Lower bound	Upper bound	Estimate	Lower bound	Upper bound	Estimate	Lower bound	Upper bound	Estimate	Lower bound	Upper bound	Estimate	Lower bound	Upper bound	Estimate	Lower bound	Upper bound
Global	-	-	-	-	-	-	3.2	1.8	5.9	5.6	3.3	9.9	5.9	4.7	7.1	10.4	8.8	12.0
High income	-	-	-	-	-	-	1.1	0.6	2.2	10.2	5.3	19.1	1.4	1.1	1.7	12.3	10.3	14.3
Upper-middle income	-	-	-	-	-	-	1.1	0.6	2.3	5.4	3.1	9.6	2.3	1.7	3.0	11.1	9.3	12.8
Lower-middle income	-	-	-	-	-	-	0.8	0.5	1.4	3.9	2.7	6.2	1.9	1.3	2.6	9.6	7.7	11.4
Low income	-	-	-	-	-	-	0.1	0.1	0.2	2.4	1.5	3.8	0.4	0.2	0.5	7.7	6.2	9.3
East Asia	-	-	-	-	-	-	0.6	0.3	1.2	5.3	3.0	9.4	1.2	0.9	1.5	10.5	8.8	12.2
Southeast Asia	-	-	-	-	-	-	0.2	0.1	0.3	3.8	2.0	6.8	0.4	0.3	0.6	9.2	7.5	11.0
Oceania	-	-	-	-	-	-	0.0	0.0	0.0	2.1	1.4	3.1	0.0	0.0	0.0	8.7	7.1	10.4
Central Asia	-	-	-	-	-	-	0.0	0.0	0.1	4.7	3.4	6.9	0.1	0.0	0.1	9.6	8.0	11.2
Eastern Europe	-	-	-	-	-	-	0.2	0.1	0.3	7.1	4.9	11.2	0.3	0.2	0.4	11.2	9.4	13.0
Central Europe	-	-	-	-	-	-	0.1	0.0	0.2	6.6	3.7	11.4	0.1	0.1	0.2	9.9	8.2	11.5
Caribbean	-	-	-	-	-	-	0.0	0.0	0.0	5.2	3.1	8.4	0.0	0.0	0.1	12.7	10.6	15.0
Central Latin America	-	-	-	-	-	-	0.1	0.0	0.2	6.4	3.6	10.8	0.2	0.1	0.2	12.6	10.6	14.8
Tropical Latin America	-	-	-	-	-	-	0.1	0.0	0.2	6.5	3.5	12.5	0.2	0.2	0.3	15.5	13.4	17.7
Andean Latin America	-	-	-	-	-	-	0.0	0.0	0.0	6.1	3.4	10.3	0.0	0.0	0.1	12.1	10.0	14.3
North Africa and Middle East	-	-	-	-	-	-	0.1	0.1	0.3	4.4	2.4	8.0	0.4	0.3	0.5	14.3	11.9	16.7
Southern Sub-Saharan Africa	-	-	-	-	-	-	0.0	0.0	0.0	3.3	2.1	5.3	0.1	0.0	0.1	8.0	6.6	9.5
Western Sub-Saharan Africa	-	-	-	-	-	-	0.1	0.0	0.2	2.2	1.3	3.5	0.2	0.1	0.3	5.1	3.9	6.3
Central Sub-Saharan Africa	-	-	-	-	-	-	0.0	0.0	0.0	2.4	1.6	3.5	0.1	0.0	0.1	7.4	5.8	9.1
Eastern Sub-Saharan Africa	-	-	-	-	-	-	0.1	0.0	0.1	2.4	1.6	3.8	0.2	0.1	0.2	6.0	4.8	7.2
South Asia	-	-	-	-	-	-	0.5	0.3	0.9	4.3	3.0	6.5	1.3	0.9	1.7	10.6	8.4	12.5
Southern Latin America	-	-	-	-	-	-	0.0	0.0	0.1	6.7	3.7	12.8	0.1	0.0	0.1	11.6	9.8	13.3
Western Europe	-	-	-	-	-	-	0.4	0.2	0.8	9.5	4.6	19.2	0.5	0.4	0.6	12.7	10.6	14.8
High-income North America	-	-	-	-	-	-	0.3	0.2	0.6	10.4	6.4	17.8	0.4	0.4	0.5	13.7	11.7	15.8
Australasia	-	-	-	-	-	-	0.0	0.0	0.0	10.6	5.5	20.6	0.0	0.0	0.0	14.9	12.6	17.3
High-income Asia Pacific	-	-	-	-	-	-	0.2	0.1	0.5	14.3	6.1	29.2	0.2	0.1	0.2	9.0	7.3	10.7

Table S1.7: The global economic burden associated with premature mortality and morbidity from mental disorders, by estimation approach and value per DALY, using alternative valuations. Dollar amounts are in trillions.

<i>Panel A: Using values per DALY of \$1,000 and \$5,000 (USD 2019)</i>									
Value per DALY (USD, 2019)	Original approach			Reallocation approach			Composite approach		
	Estimate	Lower bound	Upper bound	Estimate	Lower bound	Upper bound	Estimate	Lower bound	Upper bound
\$1,000	0.13	0.09	0.16	0.32	0.20	0.51	0.42	0.28	0.61
\$5,000	0.63	0.46	0.82	1.61	0.99	2.53	2.09	1.38	3.04

<i>Panel B: Using GDP per capita, PPP-adjusted, per DALY (international dollars, 2019)</i>									
Value per DALY (International dollar, 2019)	Original approach			Reallocation approach			Composite approach		
	Estimate	Lower bound	Upper bound	Estimate	Lower bound	Upper bound	Estimate	Lower bound	Upper bound
1x GDP PPP/capita	2.18	1.62	2.84	5.60	3.46	8.80	7.28	4.82	10.60
3x GDP PPP/capita	6.55	4.86	8.53	16.79	10.38	26.41	21.84	14.47	31.80

DALY: disability-adjusted life year. USD: United States dollar. GDP: gross domestic product. PPP: purchasing power parity.

Table S1.8: The economic burden associated with premature mortality and morbidity from mental disorders, by estimation approach and value per DALY, using alternative valuations and by World Bank income classification and GBD region. Dollar amounts are in trillions.

Panel A: Using \$1,000 per DALY (USD 2019)										
	Original approach			2016 reallocation approach			Composite approach			
	Estimate	Lower bound	Upper bound	Estimate	Lower bound	Upper bound	Estimate	Lower bound	Upper bound	
Global	0.13	0.09	0.16	0.32	0.20	0.51	0.42	0.28	0.61	
High income	0.02	0.02	0.03	0.07	0.05	0.12	0.08	0.05	0.12	
Upper-middle income	0.05	0.03	0.06	0.12	0.07	0.19	0.16	0.10	0.24	
Lower-middle income	0.04	0.03	0.06	0.11	0.06	0.17	0.15	0.09	0.23	
Low income	0.01	0.01	0.01	0.02	0.01	0.03	0.03	0.02	0.05	
East Asia	0.02	0.02	0.03	0.06	0.03	0.09	0.07	0.05	0.11	
Southeast Asia	0.01	0.01	0.01	0.02	0.01	0.04	0.03	0.02	0.05	
Oceania	-	-	-	-	-	-	-	-	-	
Central Asia	-	-	-	-	-	0.01	-	-	0.01	
Eastern Europe	-	-	-	0.01	0.01	0.02	0.02	0.01	0.02	
Central Europe	-	-	-	0.01	-	0.01	0.01	-	0.01	
Caribbean	-	-	-	-	-	-	-	-	-	
Central Latin America	-	-	0.01	0.01	0.01	0.02	0.01	0.01	0.02	
Tropical Latin America	0.01	-	0.01	0.01	0.01	0.02	0.02	0.01	0.02	
Andean Latin America	-	-	-	-	-	-	-	-	-	
North Africa and Middle East	0.01	0.01	0.01	0.02	0.01	0.04	0.03	0.02	0.05	
Southern Sub-Saharan Africa	-	-	-	-	-	-	-	-	0.01	
Western Sub-Saharan Africa	0.01	-	0.01	0.01	0.01	0.02	0.02	0.01	0.03	
Central Sub-Saharan Africa	-	-	-	-	-	0.01	0.01	-	0.01	
Eastern Sub-Saharan Africa	0.01	-	0.01	0.01	0.01	0.02	0.02	0.01	0.02	
South Asia	0.03	0.02	0.04	0.07	0.04	0.11	0.10	0.06	0.14	
Southern Latin America	-	-	-	-	-	-	-	-	0.01	
Western Europe	0.01	0.01	0.01	0.03	0.02	0.04	0.03	0.02	0.04	
High-income North America	0.01	0.01	0.01	0.03	0.02	0.04	0.03	0.02	0.04	
Australasia	-	-	-	-	-	-	-	-	-	
High-income Asia Pacific	-	-	-	0.01	0.01	0.02	0.01	0.01	0.01	

Panel B: Using \$5,000 per DALY (USD 2019)

	Original approach			2016 reallocation approach			Composite approach		
	Estimate	Lower bound	Upper bound	Estimate	Lower bound	Upper bound	Estimate	Lower bound	Upper bound
	Global	0.63	0.46	0.82	1.61	0.99	2.53	2.09	1.38
High income	0.12	0.09	0.16	0.37	0.23	0.59	0.40	0.26	0.60
Upper-middle income	0.23	0.17	0.30	0.59	0.35	0.96	0.78	0.50	1.18
Lower-middle income	0.22	0.17	0.29	0.54	0.32	0.87	0.74	0.45	1.13
Low income	0.05	0.04	0.07	0.10	0.06	0.16	0.16	0.10	0.25
East Asia	0.10	0.08	0.14	0.28	0.16	0.46	0.36	0.23	0.55
Southeast Asia	0.05	0.03	0.06	0.12	0.06	0.20	0.16	0.09	0.26
Oceania	-	-	-	-	-	-	-	-	0.01
Central Asia	0.01	-	0.01	0.02	0.01	0.03	0.02	0.01	0.04
Eastern Europe	0.02	0.01	0.02	0.07	0.05	0.10	0.08	0.05	0.12
Central Europe	0.01	0.01	0.01	0.03	0.02	0.05	0.03	0.02	0.05
Caribbean	-	-	0.01	0.01	0.01	0.01	0.01	0.01	0.02
Central Latin America	0.02	0.02	0.03	0.05	0.03	0.08	0.07	0.04	0.11
Tropical Latin America	0.03	0.02	0.03	0.06	0.03	0.09	0.08	0.06	0.12
Andean Latin America	0.01	-	0.01	0.01	0.01	0.02	0.02	0.01	0.02
North Africa and Middle East	0.05	0.04	0.07	0.11	0.06	0.18	0.16	0.10	0.24
Southern Sub-Saharan Africa	0.01	-	0.01	0.02	0.01	0.02	0.02	0.02	0.03
Western Sub-Saharan Africa	0.03	0.02	0.04	0.07	0.04	0.12	0.10	0.06	0.17
Central Sub-Saharan Africa	0.01	0.01	0.01	0.02	0.01	0.03	0.03	0.02	0.05
Eastern Sub-Saharan Africa	0.03	0.02	0.04	0.06	0.03	0.09	0.08	0.05	0.12
South Asia	0.14	0.11	0.19	0.35	0.22	0.56	0.48	0.30	0.72
Southern Latin America	0.01	-	0.01	0.02	0.01	0.02	0.02	0.01	0.03
Western Europe	0.05	0.03	0.06	0.13	0.08	0.21	0.14	0.09	0.21
High-income North America	0.04	0.03	0.05	0.14	0.09	0.20	0.14	0.10	0.21
Australasia	-	-	-	0.01	0.01	0.01	0.01	0.01	0.01
High-income Asia Pacific	0.01	0.01	0.02	0.05	0.03	0.08	0.05	0.03	0.07

Panel C: Using \ln GDP per capita, per DALY (USD 2019)

	Original approach			2016 reallocation approach			Composite approach		
	Estimate	Lower bound	Upper bound	Estimate	Lower bound	Upper bound	Estimate	Lower bound	Upper bound
Global	1.42	1.06	1.85	3.64	2.25	5.73	4.74	3.14	6.90
High income	1.12	0.83	1.46	3.46	2.19	5.41	3.72	2.45	5.48
Upper-middle income	0.40	0.29	0.52	1.04	0.62	1.69	1.37	0.87	2.07
Lower-middle income	0.10	0.07	0.13	0.24	0.14	0.38	0.32	0.20	0.49
Low income	0.01	-	0.01	0.01	0.01	0.02	0.02	0.01	0.03
East Asia	0.20	0.15	0.26	0.54	0.32	0.89	0.71	0.44	1.07
Southeast Asia	0.04	0.03	0.05	0.10	0.05	0.17	0.14	0.08	0.22
Oceania	-	-	-	-	-	-	-	-	-
Central Asia	0.01	-	0.01	0.02	0.01	0.02	0.02	0.01	0.03
Eastern Europe	0.03	0.02	0.04	0.13	0.09	0.20	0.16	0.10	0.23
Central Europe	0.03	0.02	0.03	0.08	0.05	0.14	0.10	0.06	0.15
Caribbean	0.01	-	0.01	0.01	0.01	0.02	0.02	0.01	0.03
Central Latin America	0.03	0.02	0.04	0.08	0.04	0.12	0.11	0.07	0.16
Tropical Latin America	0.04	0.03	0.06	0.10	0.06	0.16	0.14	0.10	0.20
Andean Latin America	0.01	-	0.01	0.01	0.01	0.02	0.02	0.01	0.03
North Africa and Middle East	0.08	0.06	0.10	0.16	0.09	0.26	0.23	0.14	0.36
Southern Sub-Saharan Africa	0.01	-	0.01	0.02	0.01	0.03	0.02	0.02	0.04
Western Sub-Saharan Africa	0.01	0.01	0.02	0.03	0.01	0.04	0.04	0.02	0.06
Central Sub-Saharan Africa	-	-	-	0.01	-	0.01	0.01	0.01	0.01
Eastern Sub-Saharan Africa	0.01	-	0.01	0.01	0.01	0.02	0.02	0.01	0.02
South Asia	0.05	0.04	0.07	0.13	0.08	0.21	0.18	0.11	0.27
Southern Latin America	0.01	0.01	0.02	0.04	0.02	0.06	0.04	0.03	0.06
Western Europe	0.40	0.29	0.52	1.07	0.64	1.76	1.20	0.77	1.79
High-income North America	0.51	0.38	0.66	1.72	1.15	2.58	1.84	1.24	2.65
Australasia	0.04	0.03	0.05	0.09	0.06	0.15	0.10	0.07	0.15
High-income Asia Pacific	0.10	0.08	0.13	0.37	0.22	0.62	0.34	0.22	0.52

Panel D: Using 3x GDP per capita, per DALY (USD 2019)

	Original approach			2016 reallocation approach			Composite approach		
	Estimate	Lower bound	Upper bound	Estimate	Lower bound	Upper bound	Estimate	Lower bound	Upper bound
	Global	4.27	3.17	5.55	10.93	6.76	17.20	14.22	9.42
High income	3.35	2.48	4.37	10.37	6.56	16.23	11.16	7.35	16.43
Upper-middle income	1.19	0.88	1.56	3.13	1.86	5.08	4.12	2.62	6.20
Lower-middle income	0.29	0.21	0.38	0.71	0.42	1.14	0.96	0.59	1.48
Low income	0.02	0.01	0.02	0.04	0.02	0.06	0.06	0.04	0.09
East Asia	0.61	0.46	0.79	1.63	0.96	2.67	2.12	1.33	3.20
Southeast Asia	0.12	0.09	0.15	0.30	0.16	0.52	0.42	0.24	0.67
Oceania	-	-	-	-	-	0.01	0.01	-	0.01
Central Asia	0.02	0.01	0.02	0.05	0.03	0.07	0.06	0.04	0.09
Eastern Europe	0.10	0.07	0.13	0.39	0.26	0.59	0.47	0.31	0.69
Central Europe	0.08	0.06	0.10	0.25	0.15	0.41	0.30	0.18	0.46
Caribbean	0.02	0.01	0.02	0.04	0.02	0.06	0.05	0.03	0.08
Central Latin America	0.09	0.07	0.12	0.23	0.13	0.37	0.32	0.20	0.49
Tropical Latin America	0.13	0.09	0.17	0.29	0.18	0.47	0.43	0.29	0.61
Andean Latin America	0.02	0.01	0.03	0.04	0.02	0.07	0.06	0.03	0.09
North Africa and Middle East	0.24	0.17	0.31	0.48	0.27	0.78	0.69	0.43	1.07
Southern Sub-Saharan Africa	0.02	0.01	0.03	0.05	0.03	0.08	0.07	0.05	0.11
Western Sub-Saharan Africa	0.04	0.03	0.05	0.08	0.04	0.13	0.11	0.06	0.18
Central Sub-Saharan Africa	0.01	0.01	0.01	0.02	0.01	0.03	0.03	0.02	0.04
Eastern Sub-Saharan Africa	0.02	0.01	0.02	0.03	0.02	0.05	0.05	0.03	0.07
South Asia	0.16	0.12	0.21	0.40	0.25	0.63	0.55	0.34	0.82
Southern Latin America	0.04	0.03	0.06	0.11	0.07	0.17	0.13	0.09	0.19
Western Europe	1.19	0.88	1.56	3.22	1.92	5.28	3.59	2.32	5.37
High-income North America	1.52	1.14	1.97	5.17	3.44	7.75	5.52	3.72	7.95
Australasia	0.12	0.09	0.16	0.28	0.18	0.44	0.31	0.21	0.45
High-income Asia Pacific	0.31	0.23	0.40	1.12	0.65	1.86	1.03	0.66	1.57

Panel E: Using 3x GDP per capita, PPP-adjusted, per DALY (international dollars, 2019)

	Original approach			2016 reallocation approach			Composite approach		
	Estimate	Lower bound	Upper bound	Estimate	Lower bound	Upper bound	Estimate	Lower bound	Upper bound
	Global	2.18	1.62	2.84	5.60	3.46	8.80	7.28	4.82
High income	1.27	0.94	1.66	3.88	2.44	6.11	4.22	2.76	6.23
Upper-middle income	0.78	0.58	1.02	2.05	1.23	3.33	2.70	1.71	4.06
Lower-middle income	0.31	0.23	0.40	0.75	0.45	1.20	1.02	0.63	1.56
Low income	0.02	0.01	0.02	0.04	0.02	0.06	0.06	0.03	0.09
East Asia	0.33	0.25	0.43	0.89	0.52	1.46	1.16	0.73	1.75
Southeast Asia	0.11	0.08	0.14	0.28	0.15	0.49	0.39	0.23	0.63
Oceania	-	-	-	-	-	-	-	-	-
Central Asia	0.02	0.01	0.02	0.05	0.03	0.08	0.06	0.04	0.09
Eastern Europe	0.09	0.07	0.12	0.35	0.23	0.52	0.41	0.27	0.61
Central Europe	0.05	0.04	0.07	0.18	0.11	0.29	0.21	0.13	0.32
Caribbean	0.01	-	0.01	0.02	0.01	0.02	0.02	0.01	0.04
Central Latin America	0.06	0.05	0.08	0.16	0.09	0.25	0.22	0.14	0.34
Tropical Latin America	0.08	0.06	0.10	0.17	0.10	0.28	0.25	0.17	0.36
Andean Latin America	0.01	0.01	0.02	0.03	0.02	0.04	0.04	0.02	0.06
North Africa and Middle East	0.19	0.14	0.25	0.38	0.22	0.63	0.55	0.34	0.85
Southern Sub-Saharan Africa	0.02	0.01	0.02	0.04	0.02	0.06	0.06	0.04	0.08
Western Sub-Saharan Africa	0.03	0.02	0.04	0.06	0.03	0.10	0.09	0.05	0.14
Central Sub-Saharan Africa	0.01	-	0.01	0.01	0.01	0.02	0.02	0.01	0.03
Eastern Sub-Saharan Africa	0.02	0.01	0.02	0.03	0.02	0.05	0.04	0.03	0.06
South Asia	0.18	0.13	0.24	0.45	0.27	0.70	0.61	0.38	0.91
Southern Latin America	0.03	0.02	0.04	0.07	0.05	0.12	0.09	0.06	0.13
Western Europe	0.47	0.35	0.62	1.28	0.76	2.09	1.42	0.92	2.13
High-income North America	0.51	0.38	0.66	1.73	1.15	2.60	1.85	1.25	2.67
Australasia	0.04	0.03	0.05	0.09	0.06	0.14	0.10	0.07	0.14
High-income Asia Pacific	0.12	0.09	0.15	0.43	0.25	0.71	0.40	0.25	0.60

Panel F: Using 3x GDP per capita, PPP-adjusted, per DALY (international dollars, 2019)

	Original approach			2016 reallocation approach			Composite approach		
	Estimate	Lower bound	Upper bound	Estimate	Lower bound	Upper bound	Estimate	Lower bound	Upper bound
Global	6.55	4.86	8.53	16.79	10.38	26.41	21.84	14.47	31.80
High income	3.81	2.83	4.98	11.65	7.32	18.32	12.66	8.29	18.70
Upper-middle income	2.33	1.73	3.05	6.16	3.68	9.99	8.09	5.14	12.18
Lower-middle income	0.92	0.68	1.21	2.26	1.35	3.61	3.07	1.88	4.69
Low income	0.05	0.04	0.07	0.11	0.06	0.17	0.17	0.10	0.26
East Asia	1.00	0.75	1.30	2.67	1.57	4.38	3.47	2.18	5.24
Southeast Asia	0.33	0.24	0.43	0.85	0.45	1.47	1.17	0.68	1.89
Oceania	-	-	-	0.01	-	0.01	0.01	0.01	0.01
Central Asia	0.05	0.04	0.07	0.15	0.09	0.23	0.18	0.11	0.28
Eastern Europe	0.27	0.20	0.35	1.04	0.70	1.56	1.24	0.82	1.82
Central Europe	0.16	0.12	0.21	0.53	0.32	0.87	0.63	0.39	0.97
Caribbean	0.02	0.01	0.03	0.05	0.03	0.07	0.07	0.04	0.11
Central Latin America	0.19	0.14	0.25	0.47	0.28	0.76	0.66	0.41	1.01
Tropical Latin America	0.23	0.17	0.30	0.52	0.31	0.83	0.76	0.52	1.08
Andean Latin America	0.04	0.03	0.05	0.08	0.05	0.13	0.11	0.07	0.17
North Africa and Middle East	0.57	0.42	0.75	1.14	0.65	1.88	1.66	1.03	2.56
Southern Sub-Saharan Africa	0.05	0.03	0.06	0.12	0.07	0.18	0.17	0.11	0.25
Western Sub-Saharan Africa	0.09	0.06	0.11	0.19	0.10	0.31	0.26	0.15	0.43
Central Sub-Saharan Africa	0.02	0.01	0.03	0.04	0.02	0.06	0.06	0.04	0.09
Eastern Sub-Saharan Africa	0.05	0.03	0.06	0.09	0.05	0.14	0.12	0.08	0.19
South Asia	0.55	0.40	0.71	1.34	0.82	2.10	1.82	1.13	2.73
Southern Latin America	0.09	0.07	0.12	0.22	0.14	0.35	0.28	0.19	0.40
Western Europe	1.42	1.04	1.86	3.83	2.29	6.27	4.27	2.76	6.39
High-income North America	1.53	1.14	1.99	5.20	3.46	7.80	5.55	3.74	8.00
Australasia	0.11	0.08	0.15	0.27	0.17	0.42	0.30	0.20	0.43
High-income Asia Pacific	0.35	0.26	0.46	1.29	0.76	2.14	1.20	0.76	1.81

Appendix 2

Appendix 2.1: Health system data cleaning

Overview of health system data The health facility data used in our study was obtained from Madagascar's *Gestion du Système d'Information Sanitaire* (GESIS), a Microsoft Access electronic health management information systems database.

While primary, district-level, and regional referral facilities in Madagascar all report monthly case counts of mental disorders in GESIS, case definitions vary across facilities of different levels. Disaggregated data by specific condition (e.g., depression, schizophrenia, etc.) are only reported among regional referral hospitals and university hospitals; for all other facilities, cases are reported in aggregate (e.g., "Neuro-psychic diseases" for district hospitals).

Disaggregated data is available by age; among adults, however, disaggregated data for adults ages 25 to 59 and adults 60 years and older has only been reported by primary health facilities since 2015. For all other years and all other facilities, these age categories are not separately reported. Similarly, data by sex is only reported for primary health facilities since 2015. Referrals are reported by primary health facilities and district hospitals.

A summary of the GESIS data availability is provided in Table S2.1.

Table S2.1.1: Availability of disaggregated health system data by year and level of care.

GESIS data		Primary health facilities (CSB1, CSB2, FSP)		District hospitals (CHD1, CHD2)		Regional & university hospitals (CHR, CHU)	
Years of data available		2010 - 2015		2015 - 2019		2010 - 2020	
Disease data reported by subgroup available by...	Age (bullets display which categories are available)	[2010 - 2015]		<ul style="list-style-type: none"> • Neonates: 0 to 28 days • Infants: 29 days to 11 months • Toddlers: 1 to 4 years old • Children: 5 to 14 years old • Youths: 15 to 24 years old 		[2010 - 2020]	
		<ul style="list-style-type: none"> • Adults and seniors: 25 years old and older • Seniors: 60 plus 		<ul style="list-style-type: none"> • Adults: 25 to 59 • Adults and seniors: 25 years old and older 		<ul style="list-style-type: none"> • Adults and seniors: 25 years old and older 	
Mental disorders classified (in English) as... <i>(original in French)</i>	Sex	No		Yes		No	
		Mental illnesses & psychic disorders <i>(Affections mentales et troubles psychiques)</i>		Mental disorders <i>(Troubles mentaux)</i>		Neuro-psychic diseases <i>(Maladies neuro-psychiques)</i>	
Availability of data on...	Cases	Yes		Yes		Yes	
	Referrals	Yes		Yes		—	

After compiling the GESIS data, we translated the case definitions from French to English. The translations are provided in Table S2.2.

Table S2.2: Mental health disorders reported in GESIS, in French and English

French	English ¹
Accident vasculaire cérébral	Stroke
Accidents ischémiques et cérébraux	Ischemic & cerebral accidents
Affections mentales et troubles ...	Mental illnesses & psychic disorders
Affections musculaires et neuro-...	Muscular & neuromuscular disorders (d.c.e.)
Affections musculaires primitives	Primary muscular disorders
Amyotrophie spinale	Spinal muscular atrophy
Ataxie héréditaire	Hereditary ataxia
Autres myopathies	Other myopathies
Autres pathologies neuro-psychiatriques	Other neuro-psychiatric pathologies
Autres syndromes d'algie céphalique	Other headache syndromes
Bouffées délirantes aiguës	Short-lived psychosis
Démences	Dementias
Dépression	Depression
Dystonie	Dystonia
Encéphalopathie toxique	Toxic encephalopathy
Epilepsie	Epilepsy
Hémiplégie	Hemiplegia

Hydrocéphalie	Hydrocephalus
Hystérie	Hysteria
Maladie de Parkinson	Parkinson disease
Maladies inflammatoires du Système ...	Inflammatory diseases of the central N.S.
Maladies neuro-psychiques	Neuro-psychic diseases
Méningo-encéphalites	Meningoencephalitis
Migraine	Migraine
Myasthénie et autres affections neuro...	Myasthenia gravis & other neuromuscular disorders
Neuropathie héréditaire et idiopathique	Hereditary & idiopathic neuropathy
Paralysie cérébrale infantile	Infantile cerebral palsy
Paraplégie et tétraplégie	Paraplegia & quadriplegia
Polynévrite et affections du Système ...	Polyneuritis & diseases of the peripheral N.S.
Polynévrite inflammatoire	Inflammatory polyneuritis
Polynévrites	Polyneuritis
Polynévrites au cours des Maladies ...	Polyneuritis (d.c.e.)
Psychoses aiguës	Acute psychoses
Schizophrénies	Schizophrenias
Sclérose en plaque	Multiple sclerosis
Tentative de suicide	Attempted suicide
Troubles anxieux et dépressifs mixtes	Mixed anxiety & depressive disorders
Troubles de l'humeur et de l'épisode ...	Mood & manic episode disorders
Troubles de la personnalités et du ...	Personality & behavioral disorders in adults
Troubles délirants chroniques	Chronic delusional disorders
Troubles liés à l'alcool	Alcohol-related disorders
Troubles liés au canabis	Cannabis-related disorders
Troubles mentaux	Mental disorders

¹d.c.e.: in or among diseases classified elsewhere. N.S.: nervous system

We then conducted exploratory data analysis to gauge data availability by condition, year, and facility level, which are reported in Tables S2.3-5. These tables show yearly cumulative cases of mental and neurological disorders, by facility level.

Among primary health facilities, we observed that the case definition for mental disorders changed during 2015, alongside the changes in GESIS that enabled disaggregated reporting by sex and greater disaggregation for data by age.

Among district hospitals, reporting of mental disorders has been consistent between 2010 and 2020.

Reporting of mental disorders is most detailed among regional referral hospitals (CHRRs) and

university hospitals (CHUs), with case counts reported for 40 unique conditions.

Table S2.3: Yearly cumulative cases of mental and neurological disorders reported at primary facilities

2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Mental illnesses & psychic disorders (Affections mentales et ...)									
94,507	92,805	95,171	99,743	85,212	15,491	—	—	—	—
Mental disorders (Troubles mentaux)									
—	—	—	—	—	36,044	62,812	15,311	28,404	12,276

Table S2.4: Yearly cumulative cases of mental and neurological disorders reported at district hospitals

2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Neuro-psychic diseases (Maladies neuro-psychiques)										
63,952	82,474	79,358	109,818	115,324	97,968	107,578	132,872	108,488	118,132	119,122

Table S2.5: Yearly cumulative cases of mental and neurological disorders reported at regional hospitals

2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Acute psychoses (Psychoses aiguës)												
390	942	233	217	152	334	752	395	142	61	94	120	11
Alcohol-related disorders (Troubles liés à l'alcool)												
537	676	649	388	399	238	363	570	635	393	268	250	103
Attempted suicide (Tentative de suicide)												
171	174	136	145	145	107	144	215	146	125	139	104	34
Cannabis-related disorders (Troubles liés au cannabis)												
623	1,985	283	177	155	318	436	649	716	260	428	112	38
Chronic delusional disorders (Troubles délirants ...)												
584	1,637	184	177	150	59	144	153	125	85	193	100	23
Dementias (Démences)												
44	42	29	48	39	34	143	97	36	8	4	9	2
Depression (Dépression)												
595	641	584	733	843	635	628	539	462	373	333	276	87
Dystonia (Dystonie)												
683	1,206	1,321	1,253	1,407	1,899	2,227	1,776	2,211	2,430	1,908	2,370	448
Epilepsy (Epilepsie)												
2,365	2,636	2,826	4,225	4,357	3,087	1,774	1,413	1,644	1,276	1,079	862	186
Hemiplegia (Hémiplégie)												
150	189	245	121	159	122	95	109	122	248	87	39	47
Hereditary & idiopathic neuropathy (Neuropathie héréditaire ...)												
26	8	14	34	5	16	5	9	22	27	7	17	6
Hereditary ataxia (Ataxie héréditaire)												
22	0	1	2	1	188	279	101	35	2	0	6	0
Hydrocephalus (Hydrocéphalie)												
21	64	53	24	37	30	38	24	17	19	12	9	3
Hysteria (Hystérie)												
297	207	144	204	206	347	526	313	191	234	140	131	68
Infantile cerebral palsy (Paralysie cérébrale ...)												
94	106	152	236	179	428	272	287	172	352	73	44	20

Inflammatory diseases of the central nervous system (Maladies inflammatoires ...)

54	33	43	158	73	463	694	302	21	18	4	13	0
Inflammatory polyneuritis (Polynévrite inflammatoire)												
26	108	36	15	6	5	2	11	7	5	1	13	2
Ischemic & cerebral accidents (Accidents ischémiques et ...)												
70	103	116	56	99	194	1,048	440	832	516	410	509	132
Meningoencephalitis (Méningo-encéphalites)												
15	11	14	15	10	9	29	10	14	17	3	8	1
Migraine (Migraine)												
752	1,195	1,552	1,431	1,503	1,141	1,057	1,065	1,125	1,012	793	576	177
Mixed anxiety & depressive disorders (Troubles anxieux et dé...)												
222	126	476	286	186	182	152	77	225	37	62	44	45
Mood & manic episode disorders (Troubles de l'humeur et ...)												
213	80	79	121	111	158	542	334	135	66	194	56	21
Multiple sclerosis (Sclérose en plaque)												
124	30	8	12	23	20	11	12	20	7	12	13	7
Muscular & neuromuscular disorders of diseases classified elsewhere (Affections musculaires ...)												
104	45	61	101	169	86	199	200	240	404	292	206	21
Myasthenia gravis & other neuromuscular disorders (Myasthénie et autres ...)												
150	96	152	222	269	314	279	128	311	459	288	534	64
Other headache syndromes (Autres syndromes d'algie ...)												
380	700	716	671	982	1,031	285	336	304	445	284	263	33
Other myopathies (Autres myopathies)												
72	34	46	67	41	61	225	69	65	43	47	26	3
Other neuro-psychiatric pathologies (Autres pathologies neuro-...)												
1,531	1,986	1,834	2,526	1,286	1,548	1,050	2,119	2,796	2,119	1,822	1,236	288
Paraplegia & quadriplegia (Paraplégie et tétraplégie)												
32	41	39	43	44	53	62	25	44	69	30	22	4
Parkinson disease (Maladie de Parkinson)												
48	62	45	25	22	202	596	279	33	52	17	11	6
Personality & behavioral disorders in adults (Troubles de la ...)												
207	234	183	224	135	580	1,662	1,017	142	125	194	74	18
Polyneuritis & diseases of the peripheral nervous system (Polynévrite et ...)												
316	119	62	78	59	47	42	45	28	79	95	68	20

Polyneuritis (Polynévrites)														
133	69	55	78	16	25	35	38	16	18	35	34	0		
Polyneuritis in diseases classified elsewhere (Polynévrites au cours ...)														
45	14	17	24	7	21	3	4	5	61	22	2	4		
Primary muscular disorders (Affections musculaires ...)														
37	19	10	21	10	66	118	45	112	8	54	8	66		
Schizophrenias (Schizophrénies)														
662	779	649	784	1,001	1,025	341	998	1,209	430	883	182	50		
Short-lived psychosis (Bouffées délirantes aiguës)														
162	87	75	171	102	132	255	134	65	45	19	40	8		
Spinal muscular atrophy (Amyotrophie spinale)														
7	1	0	10	0	292	1,180	744	110	0	0	0	0		
Stroke (Accident vasculaire céré...)														
345	495	498	493	369	349	264	418	450	337	262	284	78		
Toxic encephalopathy (Encéphalopathie toxique)														
47	20	30	23	39	34	20	30	47	44	7	34	13		

Data cleaning approach To address heterogeneity in reporting across primary, district-level, and regional-level facilities, our analysis constructed a single, summary outcome measure: any mental or neurological disorders reported in a given month by a given facility, irrespective of age and sex. This outcome measure was constructed by grouping our count data by facility and month-year, and then summing the incidence of mental and neurological disorders reported in GESIS within groups, preventing double counting and the inclusion of referrals in the summary measure.

Visual inspect of our data showed potential outliers. which may have arisen due to data entry mistakes, synchronization errors, and other sources. To address outliers, monthly observations of the outcome were arranged separately for each facility into a unique time series. The nonparametric Friedman's super smoother regression estimator⁶⁰ was applied to each time series to identify outlier observations and replace them through linear interpolation⁶¹. By considering outliers on a facility-by-

facility basis, the data cleaning approach preserves extreme values that may reflect true variances in incidence (for example, incidences reported by a large, regional reference hospital) while addressing potential errors in data entry. Interpolated values were coerced to the nearest integer.

Linear interpolation ultimately only impacted 2,085 of 37,260 observations of our summary outcome measure, leaving approximately 94% of observations unadjusted.

Appendix 2.2: Health facility geocoding and validation

Overview of Madagascar's health sector In Madagascar, public health facilities can be broadly classified under four types:

- **Basic** health facilities (*centre santé de base*, or CSB)
- **District** referral hospitals (*centre hospitalier de référence de district*, or CHD/CHRD)
- **Regional** referral hospitals (*centre hospitalier de référence régionale*, or CHRR)
- **University** hospitals (*centre hospitalier universitaire*, or CHU)

According to the World Bank, there were 3,246 of these facilities operating in Madagascar in 2012.⁸⁷ Of these, 3,074 were CSB facilities. CSB facilities are classified as either level 1 or 2 based on population, staffing, and services provided. Facilities may be upgraded over time, such that a CSB1 facility is converted into a CSB2. At the district level, 150 CHD facilities were functional in 2012. Like CSB facilities, CHD facilities are classified as either level 1 or level 2; these facilities provide essential medical services and—in the case of CHD2 facilities—surgical care. At the regional level, 16 CHRR and 6 CHU facilities were operational in 2012, providing specialized medical and surgical care.

In addition to these public facilities, private primary health facilities (*formations sanitaires privées de base*, or FSB) are also operational and report data to the Ministère de la Santé Publique. A USAID private health sector report identified 825 FSB facilities in Madagascar operating and providing data in 2017.⁸⁸

Sample of health facilities The sample of health facilities in our study was obtained from health facility data from Madagascar's *Gestion du Système d'Information Sanitaire* (GESIS). While the format of outputs from GESIS vary across years and facility type, there are four variables which uniquely identify facilities.

- **Region:** The region of Madagascar that contains the facility’s catchment area. All facilities have a value for this variable.
- **District:** The district of Madagascar (2nd largest administrative unit) that contains the facility’s catchment area. Only district- and commune-level facilities will have a value for this variable; regional-level hospitals have an “NA” for this variable.
- **Commune:** The commune of Madagascar (3rd largest unit) that contains the facility’s catchment area. District- and regional-level hospitals have an “NA” for this variable.
- **FS:** The facility type and name. The facility type will typically be identified with an acronym (e.g., CSB2, CHD1, etc.), with the facility name following thereafter. The facility name will occasionally be the same as the commune, district, or region that corresponds with the facility’s catchment area (e.g., CHRR Alaotra Mangoro). Some facilities are named for the village (*fokontany*) that they are located in. Other facilities are named for the groups that operate them (e.g., facilities named “EKAR” are operated by the *Eglisy Katôlika Apôstôlika Rômanina*, or the Roman Catholic Church).

Before beginning to geolocate our sample, we began by identifying the unique facilities therein. At first pass, our sample included 3,311 uniquely named facilities. We observed, however, several instances where facilities in different regions shared the same facility name: for example, there is a CSB2 facility named “Ambalabe” in both the Sava and Atsimo Atsinanana regions, which are located at the northern and southern ends of Madagascar, respectively.

These cases indicated that identifying unique facilities would require catchment area information (as well as facility name and type) to avoid erroneously classifying unique facilities as duplicates.

Using facility name, type, and catchment area to uniquely identify facilities in our sample, we identified 3,431 unique facilities. In order to classify these facilities by type, we extracted the relevant data from the “FS” variable; in doing so, we observed slight orthographic variations in the

classification of facilities types (e.g., "CSB 1" vs. "CSB1") that required standardization.

We further standardized region, district, and commune names in our sample against reference shapefiles to address variations in translation (e.g., "Atsimo" and "Sud" being the Malagasy and French words for "South"), abbreviation (e.g., "St." as an abbreviation for "Saint"), transposition (e.g., "Bevoay Beretra" transposed as "Beretra Bevoay"), accent marks (e.g., "Tovòna" vs. "Tovona"), spacing (e.g., "AmbalapaisoII" vs. "Ambalapaiso II"), separation vs. combination of names (e.g., "Tanambaovatrakaka" vs. "Tanambao Vahatrakaka"), hyphenation (e.g., "Ankiabe Salohy" and "Ankiabe-Salohy"), and spelling (e.g., "Mizilo Gare" vs. "Mizilo Gara").

A summary of the standardization changes is provided below.

Table S2.7: Standardization of district names

Name in data	Standardized name
Ambatoboeny	Ambato Boeni
Amboasary Atsimo	Amboasary-Atsimo
Ambovombe Androy	Ambovombe-Androy
Ankazoabo Atsimo	Ankazoabo
Anosibe An'ala	Anosibe-An'ala
Antanambao Manampont	Antanambao Manampontsy
Antanambao Manampotsy	Antanambao Manampontsy
Antananarivo Atsimon	Antananarivo Atsimondrano
Antananarivo Avaradr	Antananarivo Avaradrano
Antananarivo Renivoh	Antananarivo Renivohitra
Befandriana Avaratra	Befandriana Nord
Belo Tsiribihina	Belo Sur Tsiribihina
Boriziny	Port-Berge (Boriziny-Vaovao)
Fenoarivo Atsinanana	Fenerive Est
FenoarivoBe	Fenoarivobe
Fianarantsoa II	Fianarantsoa I
lalangina	Lalangina
Mananara Avaratra	Mananara-Avaratra
Midongy Atsimo	Midongy-Atsimo
Nosy Be	Nosy-Be
Nosy Boraha	Sainte Marie
Nosy Varika	Nosy-Varika
Toliara-I	Toliary-I
Toliara-II	Toliary-II
Toliara I	Toliary-I
Toliara II	Toliary-II

Tsiombe
Vohibinany
Vohimarina

Tsihombe
Brickaville
Vohemar

Table S2.8: Standardization of district names, based on commune name

Communes	District name in data	District name, updated
Antanamalaza	Antsirabe II	Ambatolampy
Antanambao Ambary	Betafo	Mandoto
Ambalamidera	Fianarantsoa I	Isandra
Andoharanomaintso	Fianarantsoa I	Isandra
Anjoma-tsara	Fianarantsoa I	Isandra
Ankarinarivo	Fianarantsoa I	Isandra
Fanjakana	Fianarantsoa I	Isandra
Iavinomby	Fianarantsoa I	Isandra
Isorana	Fianarantsoa I	Isandra
Nasandratriony	Fianarantsoa I	Isandra
Soatanana	Fianarantsoa I	Isandra
Alakamisy Ambohimahy	Fianarantsoa I	Lalangina
Ambalakely	Fianarantsoa I	Lalangina
Ambalamahasoa	Fianarantsoa I	Lalangina
Andianjanto Est	Fianarantsoa I	Lalangina
Andrainjanto Centre	Fianarantsoa I	Lalangina
Androy	Fianarantsoa I	Lalangina
Fandravandava	Fianarantsoa I	Lalangina
Ialananidro	Fianarantsoa I	Lalangina
Ivoamba	Fianarantsoa I	Lalangina
Mahatsinjo	Fianarantsoa I	Lalangina
Mahatsinjony	Fianarantsoa I	Lalangina
Sahambavy	Fianarantsoa I	Lalangina
Taindambo	Fianarantsoa I	Lalangina
Alakamisy Itenina	Fianarantsoa I	Vohibato
Andranomiditra	Fianarantsoa I	Vohibato
Andranovorivato	Fianarantsoa I	Vohibato
Ankaromalaza Mifanas	Fianarantsoa I	Vohibato
Ihazoara	Fianarantsoa I	Vohibato
Mahaditra	Fianarantsoa I	Vohibato
Mahasoabe	Fianarantsoa I	Vohibato
Maneva	Fianarantsoa I	Vohibato
Soaindrana	Fianarantsoa I	Vohibato
Talata Ampano	Fianarantsoa I	Vohibato
Vohibato Ouest	Fianarantsoa I	Vohibato
Vohimarina	Fianarantsoa I	Vohibato
Vohitrafeno	Fianarantsoa I	Vohibato
Andribavontsona	Port-Berge (Boriziny-Vaovao)	Analalava
Ambohimahavelona	Toliara-I	Toliary-II
Ambolofoty	Toliara-I	Toliary-II

Anakao	Toliara-I	Toliary-II
Analamisampy	Toliara-I	Toliary-II
Andranohinaly	Toliara-I	Toliary-II
Andranovory	Toliara-I	Toliary-II
Ankililoaka	Toliara-I	Toliary-II
Ankilimalinika	Toliara-I	Toliary-II
Beheloka	Toliara-I	Toliary-II
Behompy	Toliara-I	Toliary-II
Belalanda	Toliara-I	Toliary-II
Betsinjaka	Toliara-I	Toliary-II
Manombo	Toliara-I	Toliary-II
Manorofify	Toliara-I	Toliary-II
Marofoty	Toliara-I	Toliary-II
Maromiandra	Toliara-I	Toliary-II
Miary	Toliara-I	Toliary-II
Milenaka	Toliara-I	Toliary-II
Mitsinjo	Toliara-I	Toliary-II
Soalara	Toliara-I	Toliary-II
St Augustin	Toliara-I	Toliary-II
Tsianisiha	Toliara-I	Toliary-II
Antsahavaribe	Vohemar	Sambava

Table S2.9: Standardization of commune names

Name in data	Standardized name
Alakamisy Ambohimahy	Alakamisy Ambohimaha
Ambadrika	Ambandrika
Ambalamanasy II	Ambalamanasy II
Ambalamidera	Ambalamidera II
AmbalapaisoII	Ambalapaiso II
Ambararatabe /Nord	Ambararatabe Nord
Ambarijeby Atsimo	Ambarijeby Sud
Ambatoben'anja	Ambatoben'anjavvy
AmbatofisakaII	Ambatofisaka II
AmbatoharananaI	Ambatoharanana
Ambatolampy Tsimahaf	Ambatolampy
Ambatolampy Tsimahafotsy	Ambatolampy
Ambatoriha/Est	Ambatoriha Est
Ambatotsipihana	Ambatotsipihina
Ambatovala	Ambatolava
Ambatry	Ambartry Mitsinjo
Ambinanin'Andravory	Ambinanin'andravory
Ambinaninandro	Ambinanindrano
Ambinaniroa-Andonaka	Ambinaniroa
Ambodiadabo	Ambodiadabo M
Ambodiadabo Maitsokely	Ambodiadabo
Ambodiampana Lokoho	Ambodiampana

Ambodiampanana	Ambodiampana
Ambodifarihy	Ambodifarihy Fenomanana
Ambodihazambo	Ambodihazoambo
Ambodimanga I	Ambodimanga I
Ambodimanga II-B	Ambodimanga II
Ambodimotso Atsimo	Ambodimotso Sud
AmbodinonokaAntaratr	Ambodinonoka
Ambodirian'Isahafary	Ambodirian'i Sahafary
Ambuditandroho	Ambuditandroroho
Ambohibao Atsimo	Ambohibao Sud
Ambohibary	Ambohibary Vohilena
Ambohijato Mandritsara	Mandritsara
Ambohimahavelona	Ambohimahavelona
Ambohimalaza	Ambohimalaza Miray
Ambohimàna	Ambohimana
Ambohimanga Sud	Ambohimanga Du Sud
Ambohimanjaka	Sahatsiho Ambohimanjaka
AmbohimiarinaII	Ambohimiarina II
Ambohitralalana	Ambohitralanana
Ambohitrandriamanitr	Ambohitrandriamanitra
AmbohitsaraEst	Ambohitsara Est
Ambolidibe Atsinanana	Ambolidibe Est
Amboropotsy	Amborompotsy
Ampasimadinika	Ampasimadinika Manambolo
Ampasimbajka	Ampasimboraka
Ampasimpotsy	Ampasimpotsy Sud
Ampasipotsy Gare	Ampasipotsy Gara
Ampasipotsy Madialaz	Ampasipotsy Mandialaza
Ampataka Manampaneva	Manampaneva
Ampataka Marorenny	Ampatakamarorenny
Analalaiva	Analaiva
Analamitsivala	Analamitsivalana
Anbatomainty	Anbatomainty
Andanandava	Antanandava
Andianjanto Est	Andrainjato Est
Andimaka	Andimaky Manambolo
Andoharanomaintso	Andoharanomaitso
Andoharanomaintso	Andoharanomaitso
Andrainjanto Centre	Andrainjato Centre
Andranomiely	Rambolamasoandro Andranomiely
Andravola	Andravola Vohipeno
Andrebakely	Andrebakely Nord
Androndrone	Androndrone
Anjapaly	Anjampaly
Anjeke Ankilira	Anjeky Ankilikira
Anjeva Gare	Anjeva Gara
Anjiabe	Anjiabe Ambony
Anjiajia	Anjiajia

Anjoma-tsara	Anjoma Itsara
Anjoman'Ankona	Anjoman'ankona
Ankadinondry	Ankadinondry Sakay
Ankafina	Ankafina Tsarafidy
Ankarinarivo	Ankarinarivo Manirisoa
Ankaromalaza Mifanas	Ankaromalaza Mifanasoa
Ankasakasa	Ankasakasa Tsibiray
Ankazoabo	Ankazoabo Sud
Ankazotokana I	Ankazotokana
Ankiabe Salohy	Ankiabe-Salohy
Ankiakabe-Nord	Ankiakabe Nord
Ankilimalinika	Ankilimalinike
Ankirondro	Bemarivo Ankirondro
Anontsibe	Anontsibe Centre
Anosiarivo	Anosiarivo I
Anosy Tsararafara	Anosy Tsararafa
Antalaha	Antalaha Ambonivohitra
Antanambao I	Antanambao
Antanambao Manampotsy	Antanambao Manampontsy
Antanambaon'Amberina	Antanambaon'amberina
Antananarivo I	1er Arrondissement
Antananarivo II	2e Arrondissement
Antananarivo III	3e Arrondissement
Antananarivo IV	4e Arrondissement
Antananarivo V	5e Arrondissement
Antananarivo VI	6e Arrondissement
Antanandava Nord	Antanandava
Antananivo /Haut	Antananivo Haut
Antanetibe Mahazaza	Antanetibe
Antanimora- Sud	Antanimora Atsimo
Antenina I	Antenina
Antoby	Antoby Est
Antohaboto	Antohabato
Antokoboritelo	Marovitsika Sud
Antongo	Antongo Vaovao
Antranonkarany	Antranokarany
Antsakomanondro	Antsakoamanondro
Antsapanimahazo	Antsampanimahazo
Antsirabe I	Antsirabe Afovoany Atsinanana
Antsiranana I	Diego Suarez
Antsoantany	Antsoatany
Bealampoana	Bealampona
Bealanana I	Bealanana
Beampombo I	Beampombo I
Beandrarezona I	Beandrarezona
Befandriana-Sud	Befandriana Sud
Befandriana Avaratra	Befandriana Nord
Befetra	Befeta

Befotaka	Befotaka Sud
Befotaka Avaratra	Befotaka Nord
Behera	Behara
Belafika Haut	Belafike Haut
Belambo	Belambo Firaosana
Belaoko Marovato	Belaoka Marovato
Belo sur Mer	Belo Sur Mer
Belo Tsiribihina	Belo Sur Tsiribihina
Belotsiribihina	Belo Sur Tsiribihina
Bemaneviky H	Bemaneviky Haut Sambirano
BenatoToby	Benato Toby
Beraketa	Bereketa
Berevo Ranobe	Berevo/ranobe
Beroy Sud	Beroy Atsimo
Betioky Sud	Betioky Atsimo
Betsakotsako Andrano	Betsakotsako Andranotsara
Betsimiositra	Betsimisotra
Bevoay Beretra	Beretra Bevoay
Bevonotro	Bevonotra
Efatsy Anandroza	Efatsy
Enakara Haut	Enakara-Haut
Enaniiliha	Enaniliha
Ereda	Erada
Etrotroka	Etrotroka Atsimo
Fandravandava	Fandravandava
Faux-Cap	Betanty (Faux Cap)
Fenoeko	Fenoeko-Efita
Fieferana	Fieferana
Foulpointe	Mahavelona (Foulpointe)
Ialananidro	Ialananidro
Iavinomby	Iavonomby Vohibola
Ibity	Alatsinainy Ibity
Ihaborano Namohora	Namohora Iaborano
Iloto	Menamaty Iloto
Imady	Imerina Imady
Imeritsiatosika	Imerintsiatosika
Isaka Ivondro	Isaka-Ivondro
Isaraha	Isahara
Ivatana	Vatana
Ivato Aéroport	Ivato Aeroport
Ivony	Ivony Miaramiasa
Kalalao	Ikalaao
Kianjandrakefina	Kianjandrakefina
labohazo	Iabohazo
Lavaraty Ivondro	Ivondro
Mahafasa	Mahafasa Centre
Mahajanga I	Mahajanga
Mahatsara Lefaka	Mahatsara Iefaka

Mahatsinjo	Mahatsinjony
Mahatsinjo Atsinanana	Mahatsinjo Est
Mahazina	Mahazina Ambohipierenana
Manajary Urbain	Mananjary
Manakambahiny Est	Manakambahiny Antsinanana
Manakambahiny Ouest	Manakambahiny Andrefana
Manakara(com)	Manakara
Manambotra Sud	Manambotra Atsimo
Manapatrana	Manampatrana
Mandromodromotra	Mandromondromotra
Mangarivot	Mangarivotra
Manombo	Manombo Sud
Marintampona	Maritampona
Marivorahona	Tanambao Marivorahona
Maroarivo	Maroarivo Ankazomanga
MarofotyMarofoty	Marofoty
Maromokotra-Loky	Maromokotra Loky
Marosavoa Bas	Marosavoa
Marovitsika	Marovitsika Sud
Merimandroso	Imerimandroso
Miary	Miary Ambohibola
Mitsinjo	Mitsinjo Betanimena
Mizilo Gare	Mizilo Gara
Moramanga Urbain	Moramanga
Morarano Gare	Morarano Gara
Morombe	Cu Morombe
Nagnarena	Nanarena Besakoa
Niarovana	Niarovana Marosampanana
Nosibe Masianaka	Masianaka
Onilhy	Onilahy
Port Bergé I	Port Berge
Port Bergé II	Port Berge II
Rantabe Est	Rantabe
Rantabe Sud	Rantabe
Razanaka	Vohipeno Razanaka
Sahamadio	Sahamadio Fisakana
Sahambo	Sahambano
Sahanivotry Atsimo	Sahanivotry Manandona
Sakamahily-Ouest	Sakamahily
Sakay	Tanamarina Sakay
Sakona	Sakoana
Sambava Urbain	Sambava Cu
Sarobaratra	Sarobaratra Ifanja
Soalara	Soalara Sud
St Augustin	Saint Augustin
Talata Ampano	Tatala Ampano
Talatan'Angavo	Talata Angavo
Tanakamba	Tanakambana

Tanambao Daoud	Tanambao Daoud
Tanambaovatrakaka	Tanambao Vahatrankaka
Tanandava-Sud	Tanandava Sud
Tanandrano	Tandrano
Taolognaro	Fort-Dauphin
Toamasina Suburbain	Toamasina Suburbaine
Tovôna	Tovona
Tsarahonenana	Tsarahonenana Sahaniotry
Tsarajomoko	Tsarajomoka
Tsaratanana	Tsaratanana I
Tsiafajavona Ankarat	Tsiafajavona Ankaratra
Tsianofâna	Tsianofana
Tsinjoarivo	Tsinjoarivo Imanga
Tsiombe	Tsihombe
Tsiroanomandidy Ville	Tsiroanomandidy Fihaonana
Tsiroanomandidy Ville	Tsiroanomandidy Fihaonana
Vatolatsaky	Vatolatsaka
Vilihazo	Viliahazo
Vinaninony Avaratra	Vinaninony Atsimo
Vineta Andamasiny	Andamasiny Vineta
Zomabealoka	Zoma Bealoka

After standardizing facility types and catchment areas, the sample consisted of 3,415 unique facilities. This list of facilities was then manually inspected for any remaining duplicates. From reviewing this list, we observed that in the Diana region, the regional hospitals named “Hopitaly MANARA-PENITRA” and “Hopitaly Manara-Penitra Antsiranana” are duplicates, but appear separately because the later name contains the city the hospital is located in, Antsiranana. We standardized the names of those facilities, which resolved 2 duplicate(s).

The final sample of 3,413 unique facilities consisted of:

- 2,412 CSB facilities, including 890 CSB1s, 1,521 CSB2s, and 1 of unknown level;
- 792 FSP facilities;
- 164 district hospitals, including 52 CHD1 facilities, 42 CHD2 facilities, and 70 facilities of unknown level, and
- 45 regional hospitals, including 19 CHRRs, 8 CHUs, and 18 of unknown type.

Matching Approach Step 1: Matching to validated spatial inventory of public facilities in Sub-Saharan Africa (Maina et al.)

We began by gathering data from a validated spatial inventory of health facilities in Sub-Saharan Africa,⁶² of which 2,625 coordinates were available for public facilities in Madagascar.

In order to systematically match facilities in our sample to facilities in the spatial inventory, we implemented an approximate string matching technique. This technique—also known as “fuzzy string searching”—is a common approach to record linkage, where information from one source (e.g., our sample) needs to be linked to data from another (e.g., the spatial inventory). As its name suggests, this techniques allows for “strings” of text to be matched approximately, rather than exactly, to corresponding patterns. In our case, this can be helpful if the facility name is spelled slightly differently in our sample versus the spatial inventory, due to typographic errors in the raw data or small orthographic variations (e.g., writing “2” as “II”, inclusion or omission of a dash, etc.). A description of how this approach can be implemented in R is available at www.R-bloggers.com.⁸⁹

To account for similarly named facilities located in different regions, we constructed a full, standardized name for each facility that included facility name and catchment area prior to applying our matching technique. Facility type was standardized to align with the facility types in our sample. For example, the full, standardized name for the Alakamisy Tsarazaza Health Post located in the commune of Tsarazazaa in the Fandrian district of Amoron’I Mania region would be “Alakamisy Tsarazaza Fandrian Amoron’I Mania”, with the facility classified as a CSB1 facility).

The similarity between two strings of text can be measured numerically using the Levenshtein (or edit) distance.⁹⁰ The Levenshtein distance between two identical strings will be zero, while strings involving a single character edit (insertions, deletions or substitutions) will involve a distance of 1.

To identify the closest matches between the full, standardized facility names in our sample and the spatial inventory, we calculated a matrix identifying the pair-wise Levenshtein distance between

all possible combinations. For each member of our sample, we then selected the facility in the spatial inventory with the lowest Levenshtein distance (i.e., the nearest pair).

To maximize pair accuracy, we separately conducting matching among primary health facilities (i.e., FSPs and CSBs) and among hospitals (i.e., CHDs, CHRRs, and CHUs). For primary health facilities, the full, standardized facility names included the facility's region, district, and commune; for hospitals, the full name included the region and district only. To apply a conservative matching approach, we restricted matches to those with a Levenshtein distance no greater than 2.

Using this approach, 1,768 facilities (52%) in our sample were matched to validated coordinates, of which 1,685 facilities were matched based on identical string matches, 79 facilities were matched based on string matches with a Levenshtein distance of 1, and 25 facilities were matched based on string matches with a Levenshtein distance of 2.

Step 2: Matching to facility data from RHINoVision Decision Support System

We then gathered public health facility coordinate data from the RHINoVision Decision Support System,⁶³ which supports an open source database of health facility data in conjunction with USAID, the government of Madagascar, and other stakeholders.

RHINoVision's spatial inventory included coordinates for 3,171 primary health facilities in Madagascar.

We applied the same approximate string matching technique as in Step 1 against the RHINoVision spatial inventory, restricting matches only to primary health facilities in our sample (so as not to allow hospitals to be matched against the spatial inventory of basic health facilities).

Following visual inspection of the nearest approximate pairs, we retained matches with a maximum Levenshtein distance of 3, to allow for greater flexibility in matching.

Using this approach, 827 facilities were matched to coordinates in the RHINoVision spatial inventory, of which 677 facilities were matched based on identical string matches, 64 facilities were

matched based on string matches with a Levenshtein distance of 1, 54 facilities were matched based on string matches with a Levenshtein distance of 2, and 38 facilities were matched based on string matches with a Levenshtein distance of 3. (6 matches were duplicates and were removed.)

In total, matching to our expanded inventory in Step 2 led to 2,595 facilities (76% of our sample) being geolocated.

Step 3: Matching to any spatial sources

To geolocate the remaining facilities, we expanded our spatial inventories with health facility coordinates gathered from local consultants, the Global Healthsites Mapping Project, and other sources to create an expanded database of 13,534 uniquely identified coordinates.

We removed pharmacies from our spatial inventory, as pharmacies were not included in our sample. Removing pharmacies from our expanded spatial inventory resulted in 13,358 coordinates available for matching.

Most of the coordinates in this expanded inventory were duplicates (i.e., the same facility will appear in different sources). Importantly, coordinates for the same facility could be slightly different across sources, due to variation in precision and geolocation.

Using the same approach to uniquely identifying facilities in our sample, we grouped coordinates in our expanded inventory by facility name, type, and geographic information (namely, which commune, district, and region a coordinate fell within). In other words, in order to be grouped together, coordinates would need to be of the same facility type and name, and would need to be located in the same region and in the boundaries of the same district (for hospitals) or commune (for all other facilities).

Grouping resulted in 6,112 coordinate groups in our expanded inventory. Of these, 1,764 consisted of three or more coordinates, 762 consisted of two coordinates, and 3,586 consisted of a single coordinate.

In order to evaluate whether groups of two coordinates (which we referred to as “line groups”) and groups of three or more coordinate (“polygon groups”) were internally consistent (i.e., the points within a group were not geographically far apart, suggesting uncertainty in the location of a facility), we calculated the length (for line groups) and area (for polygon groups) of groups with more than one coordinate.

We applied an arbitrary restriction to line and polygon groups, such that the length or area, respectively, would not exceed a particular threshold. The threshold for length (15 km.) was selected to be approximately half the distance of one side of a spatial climate resolution tile (~31 km for ERA-5 data). The threshold for area (225 square km.) was assigned to be the length threshold, squared. Groups that exceeded their respective thresholds were discarded.

Among polygon groups, the mean area was 0.68 km sq, with a maximum area of 91 km sq. At the threshold of 225 square km., all polygon groups fell within the cut-off. Among line groups, the mean distance between coordinates was 1.94 km., with a maximum distance of 54 kilometers. At the threshold of 15 km., 745 line groups fell within the cut-off (98% of line groups).

After applying the thresholds, we retained 4,331 coordinate groups in our expanded inventory.

To identify a single coordinate from each group, we computed the convex hull of polygon groups and selected the centroid of the grouped coordinates. For line groups, we selected the midpoint. For groups with a single member, the coordinates of that sole member were used.

We then applied the same approximate string matching technique as in Step 1, using the remaining facilities without geolocations in our sample and the expanded spatial inventory. To maximize match accuracy, we applied the approximate string matching technique separately based on the three geographic levels of service, akin to our approach in Step 1. In other words, regional facilities in our sample are only evaluated for possible matches against regional facilities in the expanded spatial inventory, and so one for district-level facilities and for commune-level facilities.

Visual inspection of closest pairs across the regional, district, and commune level facilities indicated that likely matches had a Levenshtein distance no greater than 3.

Using this approach, 301 facilities were matched to coordinate groups in our expanded spatial inventory, including 22 regional facilities, 32 district-level facilities, and 247 commune-level facilities. In total, matching to our expanded inventory in Step 3 led to 2,896 facilities (85% of our sample) being geolocated.

Step 4: Manual matching to coordinates in the expanded spatial inventory

Despite the use of approximate string matching in Step 3 to link facilities in our sample to coordinates in our expanded spatial inventory, visual inspection and comparison of unmatched facilities to the spatial inventory revealed match failures due to variations in clinic names (e.g., “Notre Dame De Bon Remede Kiranomena” versus “Notre Dame de bon Remède”), clinic types (e.g., FSP and CSB facilities being coded interchangeably), district names (e.g., Toliary-I versus Toliary-II), and commune names (e.g., Toliara I versus Tanambao I).

We manually reviewed unmatched facilities and identified those with unambiguous matches to the spatial inventory which, for various reasons, failed to match under Step 3.

Manual matching allowed for an additional 113 facilities in our sample being linked to coordinates in our expanded spatial inventory. In total, matching to our expanded inventory in Step 4 led to 3,009 facilities (88% of our sample) being geolocated.

Step 5: Using commune and village centroids as proxies for facility locations

Among commune-level facilities, there are two potential catchment areas: communes and *fokontany* (villages). Many CSB facilities are named after the village they are located in; this provided us with additional information that could be helpful in geolocation.

While it would be ideal to obtain precise locations for each facility in our sample, for the purposes of our analysis, an approximate location would be sufficient, given the spatial resolution of the

climate data we used. The spatial resolution of ERA-5 and ESA-CCI data is approximately 30 km., meaning that all coordinates within a spatial tile of 30 km. sq. will have the same time series for a given variable. Furthermore, neighboring tiles are unlikely to have extraordinarily different time series, underscoring that close approximate locations would likely result in minimal impact to the analysis versus exact coordinates.

For commune-level facilities, knowing the catchment area may therefore be just as informative as knowing the facility's precise location if the catchment area was sufficiently small. Determining a cut-off was, again, arbitrary; to adopt a conservative threshold, we considered a catchment area small if its area was no greater than 225 square km, which corresponded to approximately 25% of the area of a climate data spatial resolution tile (Figure 23).

To exploit all available information for geolocation, we first attempted to match commune-level facilities to known *fokontany* based on the facility name and catchment area. We used approximate string matching to link facilities named for their locations in our sample to known villages; if the village area was smaller than our threshold, the centroid of the village was used as a proxy for the facility location. We then applied the same approach to unmatched commune-level facilities to known communes.

Visual inspection of village and commune matches indicated that likely matches had a Levenshtein distance no greater than 1. Using approximate string matching, we linked 56 facilities to *fokontany* with identical string matches and 4 facilities with near identical matches. After applying our threshold, 56 facilities in our sample were matched to *fokontany* centroids. We were then able to link 233 facilities to communes with identical string matches and 7 facilities with near identical matches. After applying our threshold, 201 facilities in our sample were matched to commune centroids.

Altogether, matching to centroids of communes and *fokontany* in Step 5 led to 3,266 facilities (96% of our sample) being geolocated.

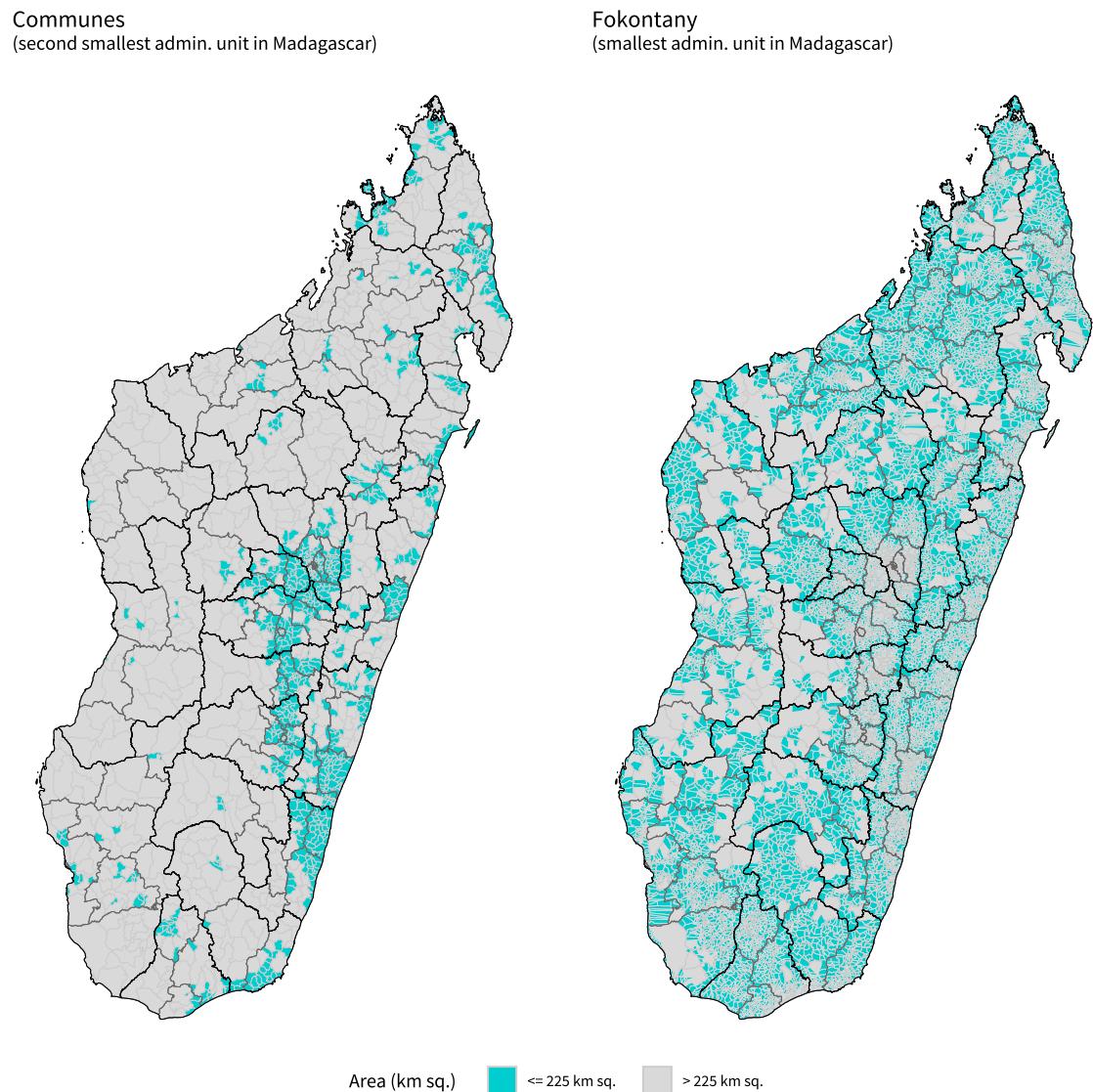


Figure 23: Communes and fokontany in Madagascar, by area. Units colored in teal are within the 225 square kilometer threshold for use in Step 5 of the matching process.

Step 6: Targeted searches

We then conducted targeted searches to identify coordinates for unmatched facilities from Google Maps, Mapcarta, and other sources. We identified coordinates for 112 unmatched facilities.

Combined with the previous steps, targeted searches led to 3,378 facilities (99% of our sample) being geolocated.

Validation To verify the accuracy of the geolocating process, we randomly selected 1% of our sample of geolocated facilities ($n = 33$) and independently identified coordinates for each facility. We then compared these coordinates to those identified from our geolocating process. We then calculated the physical distance between the independently identified coordinates and the coordinates identified from our geolocating process for each facility.

Table S2.10 provides the list of facilities in the validation sample.

Table S2.10: Sample of facilities for validation

Region	Clinic name	Longitude	Latitude
Alaotra Mangoro	MSI Ambatondrazaka	48.43	-17.83
Alaotra Mangoro	EKAR Andasibe	48.41	-18.92
Amoron I Mania	Ambohibolafotsy	47.45	-20.24
Amoron I Mania	Betsimiosotra	47.51	-20.28
Analamanga	CML Andoharanofotsy	47.53	-18.98
Analamanga	CML Finaritra Malaho	47.51	-18.97
Analamanga	Anjoma Faliarivo	47.75	-19.33
Analanjirofo	Anivorano	49.93	-16.83
Analanjirofo	Ambodivoanio	49.67	-16.18
Androy	Beraketa	45.68	-24.18
Androy	MONJA Jaona	46.08	-25.18
Androy	Antseta	45.13	-25.22
Atsimo Andrefana	Ankazomanga Ouest	44.13	-23.65
Atsimo Andrefana	Besely	44.44	-23.74
Boeny	Antsirabe	45.65	-16.83
Diana	Ambatoharana	49.04	-12.91
Diana	Marotolana	48.62	-14.02
Haute Matsiatra	Ambalakely	47.17	-21.42
Ihorombe	Ranomena	46.8	-22.7
Ihorombe	Anarabe	46.67	-23.1
Itasy	Mandiavato	47.02	-19.08
Menabe	SALFA Morondava	44.29	-20.3
Menabe	Belo Tsiribihina	44.54	-19.7
Sava	Antsahampano	49.73	-13.2
Sofia	Andranomeva	47.77	-15.8
Sofia	Ambodiadaboo	49.18	-14.65
Sofia	Ambodirafia	48.47	-14.53
Vakinankaratra	Antanimandry	46.96	-19.85
Vakinankaratra	Mandriankeniheny	47.05	-19.92
Vakinankaratra	Antsiravaza	46.86	-20.12
Vatovavy Fitovinany	Morarano Tody	47.93	-21.32
Vatovavy Fitovinany	Tataho	47.97	-22.14
Vatovavy Fitovinany	Antaretra	47.78	-21.36

Comparing the geolocated coordinates to validated coordinates for each facility, the mean distance between coordinates in the validation sample was 1.41 km., with a maximum distance of approximately 9.5 kilometers. The distance between geolocated and validated coordinates for each of the facilities in the validation sample is reported in Table S2.11.

Table S2.11: Distance between geolocated and validated coordinates

Facility name	Distance (km)
CSB1 Ambatoharana	0
CSB1 Anarabe	0
CSB1 Anjoma Faliarivo	0
CSB1 Besely	0
CSB2 Antanimandry	0
CSB2 Betsimiosotra	0
FSP CML Finaritra Malaho	0
FSP EKAR Andasibe	0
CSB2 Tataho	0
CSB2 Antaretra	0
FSP MSI Ambatondrazaka	0
CSB1 Ambohibolafotsy	0.1
FSP SALFA Morondava	0.1
CSB2 Ambalakely	0.2
CSB1 Antsiravaza	0.3
CSB1 Antsirabe	0.5
CSB2 Ankazomanga Ouest	0.5
CHRR MONJA Jaona	0.5
CSB2 Andranomeva	0.6
CSB2 Belo Tsiribihina	0.7
CSB2 Ambodivoanio	0.8
CSB2 Marotolana	0.9
CSB2 Beraketa	1
CSB2 Mandiavato	1.2
CSB1 Antsahampano	1.4
CSB1 Ambodirafia	1.4
CSB2 Ambodiadabo	1.7
CSB1 Ranomena	2
CSB2 Mandriankeniheny	4.7
CSB1 Morarano Tody	5.5
CSB1 Anivorano	5.8
CSB1 Antseta	7.2
FSP CML Andoharanofotsy	9.5

From this analysis, we drew strong confidence in the accuracy of our geolocating process and proceeded to obtain climate data for the identified coordinates in our sample.

Glossary

Translations:

- *Andrefana*: west (Malagasy)
- *Atsimo*: south (Malagasy)
- *Atsinanana*: east (Malagasy)
- *Avaratra*: north (Malagasy)
- *Est*: west (French)
- *Haute*: high (French)
- *Nord*: north (French)
- *Ouest*: west (French)
- *Sud*: south (French)
- *Vaovao*: new (Malagasy)

Acronyms:

- *CMC*: *Clinique Médico-Chirurgicale* (French), medical-surgical clinic
- *EKAR*: *Eglisy Katôlika Apôstôlika Rômanina* (Malagasy), the Roman Catholic Church
- *FJKM*: *Fiangonan'i Jesoa Kristy eto Madagasikara* (Malagasy), the Church of Jesus Christ in Madagascar
- *MSI*: MSI Reproductive Choices, formerly Marie Stopes International
- *SALFA*: *Sampanasa Loterana momba ny Fahasalamana* (Malagasy), the health care program of the Malagasy Lutheran Church