Essays on Development Challenges of Low Income Countries
Evidence from Conflict, Pest and Credit

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PhD Series 07.2022

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HANDELSHØJSKOLEN

Essays on development challenges of low income countries

Evidence from conflict, pest and credit

Myriam Noémy Marending

A Thesis presented for the degree of Doctor of Philosophy

Primary Supervisor: Mauricio Prado
Secondary Supervisor: Battista Severgnini

CBS PhD School
Copenhagen Business School

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Preface

This thesis is the result of a journey of reasoning through ideas. Many fruitful discussions at the Department of Economics at Copenhagen Business School were of invaluable input and I am grateful to all the support received from faculty and staff.

I would like to express my deep gratitude to my two supervisors Battista Severgnini and Mauricio Prado who reminded me of the red threat when I seemingly have lost it, encouraged and supported me with ingenious patience all along and left me great freedom in pursuing the questions I thought are most relevant.

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Lastly, I would like to thank my great-grandaunt Tante Idi who paved the road and showed me how to persevere and, my father who taught me the command `\phantom{}`. I would like to dedicate this thesis to you.

Abstract

This thesis discusses three distinct economic development challenges in low income countries, that stand independently. Chapter 1 looks at conflict dynamics of non-state armed groups in the context of peace agreement negotiations in Africa. Chapter 2 quantifies an environmental shock in Ethiopia and, Chapter 3 considers financialisation and informality in India.

In the first chapter "War and Peace: Measuring conflict dynamics in the presence of peace accords in Africa", I look at the behaviour of signatory armed groups during periods of peace negotiations. In particular, it assesses peace negotiations and their role for signatory, non-state military actors. It uses original matched data from ACLED and PA-X on actor-level conflict events and peace agreement signatures, covering 43 countries in Africa during 1997 and 2019. Exploiting variation in the timing of signing across actors, I employ a two-step difference-in-difference design where panel event study estimates of 24 months ex post are compared to the ones 24 months ex ante accounting for differential trend of signatory actors. The signing of an agreement is associated with large reductions in conflict prevalence and intensity in areas of previous fighting by 53% and 31% six months after the signing, respectively. In contrast, the peace agreement signature had no measurable impact on the violent activity of the signatory groups in new locations of activity ex post.

In the second chapter "Gone with the wind: the welfare effect of desert locust outbreaks", we measure the impact of desert locusts, a plants pest whose spread is caused by environmental conditions. In particular, we quantify the size of the productivity and welfare loss caused by a desert locust outbreak that hit Ethiopia in 2014. Exploiting the passive flyer nature of locusts, we identify the causal effect of locust swarms on agricultural output and children's nutritional status by modelling their movements based on wind speed and direction to distinguish areas in which they likely land (affected areas). The results show that agricultural output is significantly lower in areas hit by the shock compared to areas that are not affected. On average, children nutritional status is not negatively impacted by the shock.

The third chapter “Financial deepening and the informal economy: Evidence from local credit cycles in India” analyses the role of formal credit on the size and dynamics of the shadow economy in India, an economy with a large informal sector and large cross-sectional and time heterogeneity in bank credit availability. We use district-level bank lending data from the Reserve Bank of India from 1997 to 2018 and measure light emissions observed from outer space at night time to proxy for economic activity. The identification strategy relies on the importance of gold as a collateral commodity for credit in India. We find that gold price fluctuations have a significantly expanding effect on credit supply. Credit supply expansions lead to growth of formal GDP (with a structural elasticity between 0.1 and 0.2). According to our estimates, resources are re-allocated from the informal to the formal sector. In the short run, the contraction of the informal sector is so strong that economic output as a whole tends to fall. The economy reaps the benefits of formalization after credit becomes more easily available only over the course of 3-5 years.

Abstrakt

Denne afhandling diskuterer tre forskellige økonomiske udviklingsudfordringer i lavindkomstlande, der står uafhængigt af hinanden. Kapitel 1 ser på fredsaftaleforhandlinger i Afrika. Kapitel 2 kvantificerer et miljøchok i Etiopien, og kapitel 3 behandler finansialisering og uformalitet i Indien.

Det første kapitel, "War and Peace: Measuring conflict dynamics in the presence of peace accords in Africa", ser på dynamikker i civilkonflikter i perioder med fredsforhandlinger. Den vurderer især fredsaftaleforhandlinger og deres rolle for underskrivende, ikke-statslige militære aktører. Den bruger originale data om konflikthændelser på aktørniveau og fredsaftalesignaturer, matchet mellem ACLED og PA-X, der dækker 43 lande i Afrika i løbet af 1997 og 2019. Ved at udnytte variation i timingen for underskrivelse på tværs af aktører bruger jeg en difference-in-difference design, hvor estimater for panelbegivenhedsundersøgelser på 24 måneder ex post sammenlignes med de 24 måneders ex ante, der tager højde for den differentierede tendens blandt underskrivende aktører. Underskrivelsen af en aftale er forbundet med store reduktioner i konfliktprævalens og intensitet i områder med tidligere kampe med henholdsvis 53% og 31% seks måneder efter underskrivelsen. I modsætning hertil havde undertegnelsen af fredsaftalen ingen målbar indvirkning på de underskrivende gruppers voldelige aktivitet på nye aktivitetssteder ex post.

Andet kapitel "Gone with the wind: the welfare effect of desert locust outbreaks" måler velfærdseffekten af et skadedyr, der hovedsageligt er forårsaget af miljøforhold. Udbrud af ørkenvandregræshopper og andre skadedyr udgør en betydelig trussel mod fødevaresikkerheden for millioner af mennesker. I denne artikel kvantificerer vi størrelsen af produktivitets- og velfærdstab forårsaget af et ørkengræshoppeudbrud, der ramte Etiopien i 2014. Vi identificerer årsagsvirkningen af græshoppesværme på landbrugsproduktionen og børns ernæringsstatus ved at modellere deres bevægelser baseret på vindhastighed og vindretning at skelne mellem områder, hvor de sandsynligvis lander (berørte områder). Vi oplever, at landbrugsproduktionen er markant lavere i områder, der er ramt af chokket, sammenlignet med områder, der ikke er berørt.

I gennemsnit påvirkes børns ernæringsstatus ikke negativt af chokket.

Det tredje kapitel "Financial deepening and the informal economy: Evidence from local credit cycles in India" analyserer den formelle låns rolle på størrelsen og dynamikken af skygge- økonomien i Indien, en økonomi med en stor uformel sektor og stor tværsnits- og tidsmæssig heterogenitet i bankkredittilgængeligheden. Vi bruger bankudlånsdata på distriktsniveau fra Reserve Bank of India fra 1997 til 2018 og måler lysemissioner observeret fra det ydre rum om natten for at vise økonomisk aktivitet. Identifikationsstrategien er afhængig af vigtigheden af guld som sikkerhedsstillelse for kredit i Indien. Vi finder, at udsving i guldprisen har en markant udvidende effekt på kreditudbuddet. Kreditudbudsudvidelser fører til vækst i formelt BNP (med en strukturel elasticitet mellem 0,1 og 0,2). Ifølge vores estimater omfordeles ressourcer fra den uformelle til den formelle sektor. På kort sigt er nedgangen i den uformelle sektor så kraftig, at den økonomiske produktion som helhed har tendens til at falde. Økonomien høster fordelene ved formalisering, efter at kredit først bliver lettere tilgængelig i løbet af 3-5 år.

Introduction

This thesis contributes to the literature of development economics from three different angles. The first chapter relates to the large literature on civil conflict and peace negotiations, in particular the more recent literature on armed group-level dynamics in Africa. The second chapter contributes to strands of literature that measure the impact of plants pests on household level measures of welfare and broadly associates to household and individual level responses to income shocks in low income countries. The third chapter links to the discussion of financial frictions and the (mis-)allocation of resources across sectors and thus the variation in total factor productivity and living standards across countries.

Firstly, wars are costly, violent shocks that often only are the entry point of very long periods of change. Institutionalised peace processes are a frequently used policy tool intended to reduce conflict.

The literature on peace agreement and conflict is riddled by endogeneity concerns (Rohner, 2018). One way to advance in the direction of identification is to improve the dataset granularity of peace agreement information and match it to the temporal and spatial level of granularity of the conflict data. I construct an original dataset matching the peace agreements from the PA-X dataset to the actors of the ACLED dataset, (Bell et al., 2020; Raleigh et al., 2010). This novel, actor-level based dataset allows me to study spatial and temporal aspects of violence committed by signatory and non-signatory actors in the context of Africa, at a unique actor-month-grid-cell level.

Chapter 1 investigates the impact of peace agreement on the behaviour of signatory, non- state military actors in Africa during 1997 and 2019. Specifically, it considers to what degree an actor's behaviour changes in anticipation of the formal end of the negotiation phase, and its respective abiding behaviour in terms of reduction in violence thereafter. Including actor, grid-cell and month fixed effects, the empirical analysis employs a difference-in-difference design exploiting panel variations in violence around the timing of the signing of the agreement.

The findings shed light on the spatial and temporal nature of concluded deals' effectiveness to decrease violence committed by signatory actors. In particular, the analysis finds evidence that the association between peace agreement signature and reduction in violence is mediated by location of activity. In grid-cells with activity ex ante a measurable reduction is found, in contrast to the finding across all grid-cells where peace agreement signature is associated with no significant change in violent behaviour post signing.

Secondly, farm households in low income countries are often exposed to large negative productivity shocks, among them rapidly spreading desert locust pests. Recently, a massive desert locust upsurge in Eastern Africa, Southwest Asia and around the Red Sea has been declared as one of FAO's highest priorities.

The measurement of desert locusts so far focused on uniform distributional buffer zones around the observed location on the ground. In Chapter 2, together with Stefano Tripodi, we advance their measurement by modelling flight trajectories of locust swarms as if they were particles in the atmosphere using NOAA's HYSPLIT model. We corroborate our findings by using an alternative measure of exposure, in the spirit of (Borusyak and Hull, 2021), that removes the bias due to the possibility of non-random exposure to desert locust swarms.

We find that being exposed to desert locust swarms is associated with a decrease of 10-11% in output of total and subsistence crops. This is a considerable effect given the impact is measured two harvesting seasons after the swarms infestation.

Thirdly, access to financing is the single-most named obstacle for firms to produce, and almost twice as important for informal compared to formal firms (La Porta and Shleifer, 2014). Informal firms account for a large share of economic activity and provide livelihood for billions of people worldwide.

To address the potential endogeneity of financial development and determinants of the informal economy, the literature exploited regulatory frameworks in banking availability or the use of a panel VAR approach. In Chapter 3, together with Gabriel Züllig, we exploit gold price variations to examines to what extent the positive effects of access to credit on formal output is simply a matter of reallocation of resources to the formal economy or whether it represents an increase of total economic activity.

Using district- level credit data from the Reserve Bank of India between 1998 and 2017, we show that a 10% increase in the gold price leads to a 1.5% increase in credit in the short run and 4% higher lending in the medium run. We also estimate a dynamic response of GDP to the same shock: It expands over time with a structural elasticity with respect to credit supply between 0.1 and 0.2.

Chapter 1

War and Peace: Measuring conflict dynamics in the presence of peace accords in Africa

1. War and Peace: Measuring conflict dynamics in the presence of peace accords in Africa

Summary
This paper assesses peace agreement negotiations and their role for signatory, non-state military actors. It uses original data on actor-level conflict events and peace agreement signatures, matched between ACLED and PAX covering 43 countries in Africa during 1997 and 2019. Exploiting variation in the timing of signing across actors, I employ a two-step difference-in-difference design where panel event study estimates of 24 months ex post are compared to the ones 24 months ex ante accounting for differential trend of signatory actors. The results reveal two counter-vailing forces, on the one hand an increase in fighting (prevalence and intensity) during the months ahead of signing a peace agreement and on the other hand, a decrease thereafter. The latter associates a peace agreement with reductions in conflict prevalence and intensity in areas of previous fighting by 53% and 31% six months after the signing, respectively, compared to the month of signing. In contrast, the peace agreement signature had no measurable impact on the violent activity of the signatory groups in new locations of activity ex post.

1.1 Introduction

Wars are costly, violent shocks to both society and the economy that often lead as an entry point into very long periods of change. The loss in terms of human fatalities, destruction and damage to social structures and human capital is often times irreversible and felt most by the poorest and most vulnerable households (Bank, 2011).[1]

In an effort to reduce conflict, international interventions target state-building capacities and peace-building initiatives.[2] At the microlevel, peace negotiations and consequent agreements represent a policy tool to directly handle conflict warring parties. They constitute a political channel of the bargaining position, while offering a window

[1] Wars negatively impact educational outcomes, decrease inter-ethnic trust and generally hurt physical and mental health, (e.g. Shemyakina, 2011; Rohner et al., 2013; Barenbaum et al., 2004). It is the United Nations Sustainable Development Goals 16.1 that targets to "significantly reduce all forms of violence and related death rates everywhere".

[2] The OECD Development Assistance Committee spent 68.2 billion USD in 2016 in fragile countries, and targeted interventions by the United Nations Peacekeeping operations approved a budget of 6.38 billion USD for the fiscal year 2021/22, UN Peacekeeping. This in contrast, to the world military expenditures, estimated at 1981 billion USD for the year 2020, SIPRI Yearbook.

of opportunity to consolidate control for the actors involved. As peace agreements are a consequence of local conflict dynamics, assessing their impact is riddled with endogeneity and limited rigorous knowledge as to which agreements have most effect and if the implied mechanisms actually exists.[3]

This paper investigates the impact of peace agreement on the behaviour of signatory, non-state military actors. Specifically, I consider to what degree an actor's behaviour changes in anticipation of the formal end of the negotiation phase, and it's respective abiding behaviour in terms of reduction in violence thereafter. The outcome of interest is conflict prevalence as a binary indicator variable and conflict intensity as log events and log conflict deaths at the actor level around the timing of the signature in 43 African countries. The empirical analysis is based on an original dataset where I match the actors from the Armed Conflict Location and Event Data Project, ACLED, with the signatories of the PAX Peace Agreement Database in Africa during 1997-2019.[4] This novel, actor-level based dataset allowed me to study spatial and temporal aspects of violence committed by signatory and non-signatory actors. There are 642 agreements signed between May 1990 and December 2019, of which I match 78% on actor name only and 15% based on spatial information, with a complete match of all actors involved in 43% of the agreements.

I spatially disaggregate the data at a 0.5×0.5 arc degree grid-cell,[5] armed actor level of observation and on a monthly frequency during the lifetime of an actor. Including actor, grid-cell and month fixed effects, the empirical analysis looks at within-actor and within-area panel variations in violence around the time of the signing of the agreement. In particular, it exploits time variation in the signing of peace deals across actors and countries in an event study approach, following the literature that looks at the effects of policies. In the context of those signatory actors considered, the event study shows a clear upward trend of violence prior to the signing. To address the existence of pre-trends in interpreting the effect of peace agreement on violence, I follow Greenstone and Hanna (2014) and test the estimated event study coefficients for a trend break at the time of signing. Essentially, I use a two step difference-in-difference style design to compare ex post to ex ante in presence of upward trending ex ante violence outcomes.

[3] A peace agreement represents the final version of a negotiated political deal among conflictual parties after months or years of negotiation, in cross-section its content varies in terms of concessions made and provisions included, e.g. political, economic power-sharing, security sector reforms (Bell et al., 2020).

[4] The ACLED dataset collects individual level data on conflict events in different regions globally, (Raleigh et al., 2010), and PAX is an extensive dataset on peace agreements globally with characteristics on content and actors involved (Bell et al., 2020).

[5] A grid of 0.5×0.5 arc degrees translates to grid-cells of around 55×55 km at the equator.

The analysis indicates that concluding a negotiation phase with a peace agreement and parties agreeing to its terms by signing the document, can be effective in reducing violence (prevalence and intensity) in locations that were dominantly affected by violence ex ante. In contrast, the findings suggest that the signatory non-state groups may dislocate away from these locations post signature with little effect on violence in the new areas. Independent of location of activity, there is weak evidence to suggest that the signatory actor changes its violent activity post signature compared to its average behaviour during the 24 months before signing.

In particular, the conclusion of a peace negotiation with an agreement is associated with large reductions in conflict prevalence and intensity in areas of previous fighting by 53% and 31%, respectively, six months after the signing. The results are robust against sensitivity checks including non-signatory actors as pure controls in the estimation. The negative effect on violence found in locations of activity ex ante reflects on the one hand, an observed overall increase in violence (prevalence and intensity) in the months ahead of signing compared to the month of concluding the deal; while on the other hand, it suggests that the agreement's effect is bound locally and does not extend to new locations of signatory groups' activity.

These findings shed light on the spatial and temporal nature of concluded deals' effectiveness to decrease violence committed by signatory actors. Furthermore, it poses the question as to whether incentive structures in peace deals may be associated with perverse effects during their negotiation phase.

Peace agreements' content and their signing are of inherently endogenous nature to past and current conflict dynamics, and in the presence of strong pre-trends I do not identify the effect of peace agreement signature on non-state military actors' behaviour in general. The setting studied does instead allow to evaluate the effect on signatory actors, but is not able to consider spillovers to non-signatory actors due to selection concerns into signing. Furthermore, the study is limited to the effects from the signing of peace agreements and does not consider peacekeeping operations and overall peace processes in general.

The inherent concern of endogeneity and the measuring of the impact of settlements on conflict remains largely unaddressed in the existing literature, see Rohner (2018) for an extensive overview. There is consensus that the design of peace agreements and their composition in terms of clauses and provisions are a crucial aspect in the assessment of an agreement's success measured in terms of fatalities prevented and peace duration (e.g. Badran, 2014; Joshi and Quinn, 2015). In addition, I examine whether incentive structures from different agreement types impact a signatory actor's behaviour differently across time, where ceasefires are more likely to be followed by another agreement, rather than substantive framework agreements.

The paper also draws on the considerable body of literature on civil conflict,[6] in particular, focusing on armed group level dynamics (Kalyvas, 2006), addressing network interdependence in armed groups' conflict effort (König et al., 2017) and strategic considerations in actors' behaviour in terms of alliance forging or organisational choices (size) to be dependent on whether the prize at stake is public or private in nature (e.g. Christia, 2012; Staniland, 2012; Mayoral and Ray, 2021). These findings encourage the interpretation of violence as a strategic decision, as exemplified in the context of negotiations and reaching a settlement amongst a landscape of competing parties. Additionally, the study aligns with the strand of literature that examines civil conflict exploiting the spatial and temporal attributes of fighting, (e.g. Berman et al., 2017; Harari and La Ferrara, 2018).

The paper contributes to the literature in several ways. I study peace agreements and conflict; (i) where I focus on the evaluation of peace agreements on the behaviour of signatory groups; (ii) for the first and last agreement per actor; (iii) using novel data at a high spatial and temporal resolution; and (iv) covering 43 countries in Africa between 1997 and 2019. Furthermore, I provide evidence that reductions in violence measured after signing a peace agreement have a distinctive spatial pattern driven by relocation of signatory actors.

The paper is organised as follows. Section 1.2 provides a synopsis of non-state military actors' behaviour, and presents key arguments on the impact of peace negotiations on the central struggle of power distribution among armed actors. Section 1.3 presents the different data sources used and examines descriptive statistics on signatory actors. Section 1.4 lays out the empirical strategy to evaluate the effect of peace agreement signature on violence. Section 1.5 reports estimates on the effect, and discusses alternative specifications and, in Section 1.6 I draw my conclusions and discuss potential avenues for future research.

1.2 Background

1.2.1 Non-state military actors

Conflict remains prevalent especially in Africa. An estimated 716085 direct fatalities occurred in events of political violence registered in the Armed Conflict Location and

[6] A relevant overview of the earlier literature is given by Blattman and Miguel (2010), complemented and put in perspective of peace negotiation see Rohner (2018).

Event Data Project (Raleigh et al., 2010) between 1997 and 2019, of which 64% in battles, 26% in violence against civilians and 7.7% in explosions or remote violence events.[7] Yet, these costs alone do not ensure that there exists a mutually preferable settlement as information and political bias may introduce distortions as do other motivational factors to take up arms.

In particular, the following factors have been found to prolong conflict and prevent to settle for peace easily, most prominently: natural resources (e.g. Fearon, 2004; Berman et al., 2017); peripheral territory under control of rebel/armed groups (e.g. Cunningham et al., 2009; Kalyvas, 2006); the presence of a large number of actors (e.g. Cunningham, 2006, 2013); ethno-political exclusion of groups (e.g. Wucherpfennig et al., 2012; Fearon, 2004).

In the context studied, civil wars have seen an increasing number of non-state military actors[8] engaged in violence, also reflected in an increasing number of signatories per agreement. New groups join the battle, but importantly existing groups also opt for regrouping in order to survive. Besides dynamics in group's behaviour with respect to size, alliances, it operates spatially. On the one side we observe a larger degree of mobility of armed actors, e.g. short run hit-and-run tactics, displacement over the medium ran. Factors of fluidity in temporal and spatial aspects of non-state military actor's behaviour may be at odd with traditional negotiation and implementation, bound to the same actor and place over time.

1.2.2 Peace agreements

Peace agreements have in common to contain an initial deal on at least one subject, as minimal as "talking about how they are going to talk" to parties agreeing on to building lasting peace through power-sharing arrangements, economic development projects, security sector reform and extensive post-conflict reconstruction activities including disarmament, demobilization and reintegration (DDR). Effectively, the differences are observed by nature of agreement stage and provisions, mechanisms entailed in the text. PAX distinguishes the following seven stages: pre-negotiation or pre-process; substantive - comprehensive; substantive - partial; implementation or renegotiation; renewal; ceasefire; other (Bell et al., 2020). Each peace process is individual and may not make use of different stages gradually, e.g. rather a group may

[7] The number including also indirect fatalities such as the spread of diseases, is likely to be significantly larger. Ghobarah et al. (2003) shows that including indirect fatalities, the numbers of people that died between 1945 and 1999, estimated at 3.3 and 16.2 million due to interstate and civil wars, respectively, would more than double.

[8] Based on (Staniland, 2017) a non-state military actor is defined as a unit of fighters, equipped with weaponry under control of a formal leadership structure, that appears as a coherent actor, interacts with the government or other non-state military actors.

sign consecutively several ceasefire agreements and never sign a substantial framework type of treaty. Therefore, the PAX agreement stages reflect the content discussed and generally what is at stake as a consequence of it. Several agreements can address the same conflict, incompatibility subsequently in the same year or over several years.

A peace process window on average lasts about 4 years (Prorok and Cil, 2021). PAX includes agreements that are clearly signed or agreed, and disregards agreements that are signed by one side and not the other with no clear subsequent status. I do not observe negotiations that fail to reach a signed agreement. The reasons for negotiation failure are overlapping with the reasons for bargaining failure explaining conflict occurrence in the first place: asymmetric information about an opponent's military capabilities and the inherent commitment problem of warring parties to obstruct a peaceful settlement (Fearon, 1995).

The literature measures success of peace agreements along three distinct dimensions of fatalities prevented, peace duration (the dominant criterion) and economic recovery after the signing of a settlement (Rohner, 2018).

A signatory actor can sign over its lifetime more than one agreement, including several text that were subject of separate negotiations and signatures, yet addressing the same conflict. In the sample studied, there are on average 7 agreements per actor, that are collapsed at the monthly level and where only the first and last agreement per actor are looked at.

1.3 Data

This section provides information about the main data sources and variables used in the paper. To study local conflict dynamics in the presence of peace agreements, I merge the signatory actors of the PAX peace agreement dataset with the armed actors in the ACLED conflict data. More details appear in the Appendix Section A.

The baseline structure of the dataset consists of an unbalanced panel of armed group-level data at a monthly frequency that spans from 1997 to 2019 and covers countries in Africa that signed at least one peace agreement addressing a domestic civil conflict during said time period.

1.3.1 Armed group-level data

The conflict data is taken from the Armed Conflict Location and Event Data Project, ACLED, (Raleigh et al., 2010), which provides details on all political violence events in Africa starting in 1997 until present. For each event, it reports information on the actors involved (main actors on opposing sides and their potential associated actors), the location, the date (the precise day in most cases) and the type of event.[9]

A unique feature of the dataset is that it records all political violence events independent of battle-related death thresholds, hence it is particularly well suited to track individual armed groups' movements across space and time. The analysis focuses on conflict events, excluding protests and riots from the main sample.

Non-state military actors as defined above (Section 1.2.1) are identified in the data as actors that are coded in at least one military activity as main actor during their observed live span and are labelled with a unique name that distinguishes them from unidentified armed groups.[10] A distinction is made among the non-state military actors with respect to eligibility to sign a peace agreement. Actors are *eligible* when based on current political, legal procedures, allowing them to participate in official, national peace negotiations. Most prominent excluded parties include jihadi groups.[11] As such, consequent analysis will be limited to *eligible* non-state military actors, excluding identified jihadi groups as well as "unidentified armed groups".

To identify the area most likely under an actor's control, *homeland* areas are designated, encompassing in a concave hull all unique conflict event locations over two years per country, excluding strategic events such as the signing of peace agreements in foreign cities, where no ties otherwise exist. Based on these polygons I construct measures to proxy the *size* of a group: area homeland (km^2), length of the longest diagonal (km), where larger numbers are positively associated with an actor's influence, relevance depicting military capacities to cover larger stretches of land or access a larger pool of resources.

Furthermore, a group's *allies* and *enemies* are coded based on the relational aspect of the events: direct allies fight on the same side and indirect allies are the enemies' direct enemies; direct enemies fight on opposite sides, and indirect enemies are the enemies'

[9] Political violence is defined as "the use of force by a group with political purpose or motivation" (Raleigh et al., 2010). Each event involves designated actors that are classified according to the following typology: government force; rebel force; political militia; ethnic militia; rioters; protesters; civilians; outside/external force (e.g. missions, military operations by the AU (AMIS in Sudan), the UN (MINUSMA in Mali), the EU (EUFOR in CAR) or by foreign countries (French Barkhane in Mali, G5Sahel in the Sahel). The events are divided into six different types with subgroups: battle; attack against civilians; explosion/remote violence; strategic development (e.g. establishment of headquarters); protesting and rioting.

[10] This excludes besides all state actors, e.g. government, (inter)national security actors, non-state actors of the following: purely criminal organisations (e.g. bandits, trafficker), unidentified armed groups, protesters, rioters, civilians, and international actors (NGOs, interest groups).

[11] The (international) discourse is against the formal inclusion of jihadi groups in peace negotiations as of now, see for example the French communication with respect to peace talks with JNIM or Ansar Dine in Mali. In the context of the countries studied, the activities of jihadi groups represent a growing share of all violent events registered, and are responsible for the deadliest attacks in recent years.

direct allies. A group's *ally* (direct and indirect) is defined to never fight against that group and at least two times directly or indirectly with said group, while a group's *enemy* is defined to always fight against that group with at least two observed ACLED events directly and/or indirectly.[12]

The main outcome studied is prevalence and intensity of conflict at the monthly actor level, where *conflict prevalence* is a binary indicator variable whether the actor was involved in any conflict event and zero otherwise, and *conflict intensity* is measured as log count of conflict events or log count of fatalities.

ACLED relies on a wide range of local, regional and national sources. Measurement error is of concern if correlated with conflict or peace agreement likelihood. I account for bias resulting from across grid-cell and time by including respective fixed effects in the estimation.

1.3.2 Peace agreement data

The data on peace deals comes from the Peace Agreement Database, PAX, (Bell et al., 2020), it covers agreements signed or agreed globally since 1990 until present. It includes agreements between state actors, state versus non-state actors, or non-state versus non-state actors, where the latter two are subject of this paper.[13]

The dataset distinguishes the treaties into seven categories based on the stage they are in and specifies the names of the relevant parties (signatories, mediators, guarantors). Provisions of the agreements are coded into multiple categorical and dummy variables, among them included in the analysis are: power sharing (political, territorial, economic and military), socio-economic reform/ reconstruction (e.g. development programmes, aid, land reform), and implementation mechanisms.

It is the most complete database on peace agreements available, including agreements independent of any battle-related death threshold per year, yet, to the best of my knowledge it has not been matched with the ACLED conflict dataset before.[14]

The signatory actors, the parties signing the document at the end and agreeing to its terms, are matched by name with the actors from the ACLED dataset. In the ma-

[12] König et al. (2017) employ a network analysis using allies and enemies in combat, as well as their homelands, both similarly defined as in this paper. They consider the same dataset and look at the context of the Democratic Republic of the Congo.

[13] Original sources of PAX are existing collections (e.g. UCDP, UN Peace Agreement Database); country-specific websites and literature; websites of other civic groups; official documentation of international organisations; and writing to or meeting with and requesting documentation from governments and actors who have signed peace agreements, or mediators involved in conflicts.

[14] The UCDP Peace Agreement Dataset contains a subsample of agreements compared to the PAX, but it is directly linked to the UCDP conflict dyads data and contains information to what degree the agreement addresses the warring parties incompatibilities, (Pettersson et al., 2019).

jority of cases the names do not match directly, largely due to different languages (e.g. French vs English) and an actor being called several names. I expert coded these cases using news article, reports by humanitarian organisations or to a limited degree academic articles. Group fragmentation and group unification, when identified, is matched with respect to timing as well as possible events between those primary ACLED events and signed peace agreements. Lastly, were coalitions to sign a deal and it was known that the individual members were active before or during the negotiation phase, I code each member as separate signatory, and thus consider conflict events individually by signatory. Geographical matching is used in absence of any match by corresponding actor name in ACLED, e.g. in case the signatories are local chiefs or communities, as well as to limit a larger group to its subsidiary that signed in its name and is active only locally.

Between May 1990 and December 2019 PAX registers 642 agreements signed in Africa, of which 13% are between states, 64% have at least one non-state actor as signatory and, 23% are between non-state actors in a local conflict setting. Of the 642 agreements signed, I matched 78% on actor name only and 15% based on spatial information, with a complete match of all actors involved in 43% of the agreements. The 44 unidentified agreements are predominantly treaties between political parties, or address conflicts and corresponding actors that are not active anymore post 1997, the beginning of the ACLED data registration. Figure 1.1 illustrates the match in terms of actors matched between PAX and ACLED for the sample used in this study.

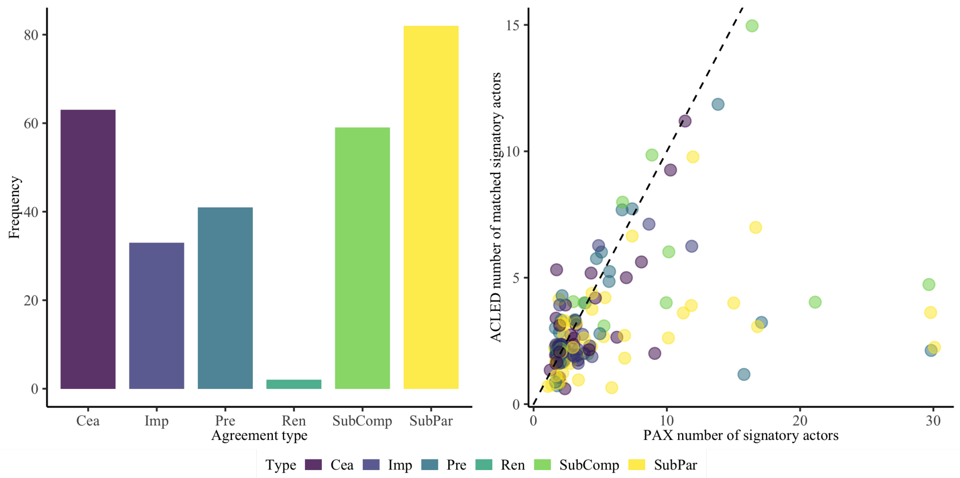
The analysis is restricted to the agreements where at least one signatory actor is a non-state military actor largely limiting respective conflicts to within a state's borders, this identifies 129 unique non-state military actors. To account for the fact that 60% of non-state signatory actors, have signed at least two different agreements during the sample period considered, the sample is limited to the first and last agreement per signatory, while the latter is the same as the former in 40% of the actor-agreement combination included.[15] The selection of first and last agreement allows for a sample of 234 unique peace agreements and limits influence from other agreements being signed in close succession in the ex ante period of the first agreement and similarly, for the ex post period of the last agreement.

1.3.3 Sample characteristics

Table 1.1 describes actor sample characteristics observed across time and locations of activities aggregated at grid-cells of a resolution of 0.5×0.5 arc degrees. The sample

[15] This does not account for the fact that an actor is a potential signatory to an agreement before or after the sample period.

Figure 1.1: Peace agreement type and number of signatory matched between PAX and ACLED included in the sample



Notes: This figure illustrates the 234 matched agreements employed in the analysis of first and last deals per actor during the sample period 1997 and 2019. The left panel shows a frequency plot of the different agreement types: Ceasefire (Cea), Implementation (Imp), Pre-negotiation (Pre), Renewal (Ren), Comprehensive framework (SubComp), Partial framework (SubPar). The scatterplot in the right panel illustrates the quality of match, where a 100% fit between PAX and ACLED would rest on the 45 degrees dashed line. The associated R^2 statistic is 0.82. The "over-matching', where more ACLED actors are matched than PAX actors, is largely caused by typos in ACLED names such that one PAX actor fits several ACLED names, but only one ACLED id.

period spans from 1997 to 2019, measured at a monthly frequency.

The sample is restricted to non-state military actors that are likely eligible to participate in peace negotiation and sign an agreement, as defined above. This allows to consider a sample of groups that satisfy minimal requirements of organisational structure, while actively engaged in armed conflict as the main actor at least twice during the sample period.

Furthermore, the observations of military activity are restricted by the timing of peace agreement signatures, limited to the first and last treaty per actor during the sample period within a temporal window of 24 months before and after each signing. To separately consider the first and last agreement signed allows an examination of both ex ante and ex post dynamics, largely without noise from other agreements being signed less than 24 months apart. The window considered is large enough to detect trends, covers initial negotiation and at least the beginning of the implementation phase.[16]

[16] Peace processes last on average 41 months, with a minimum of two and maximum of 205 according to Implementation of Peace Agreements Dataset (Prorok and Cil, 2021).

Based on the sample selection the baseline analysis considers 1465 actors out of 9795 identified state and non-state actors (based on distinctive names over time), of which 156 have signed at least one peace agreement. The violent activities included intersect with 3384 unique grid-cells at 0.5×0.5 arc degree resolution.

The actors are observed in conduct of violent activities on average over a lifespan of 11.5 years, with at least 16 months before signing or being active in a country of peace agreement signature (see Table 1.1 Panel A).

Conflict events at the actor, month, grid-cell level are relatively rare, resulting in a sample mean of 0.07 for conflict prevalence and 0.14 for intensity with higher measures for signatory groups. The event types are classified as battles in 40% of the cases, as strategic developments in 10%, as violence against civilians in 38% and as explosions/remote violence in 12% of the cases. A majority of the violent events, 64%, do not cause any direct combat fatalities.[17] The majority of activity is observed in the countries of origin of the actors, as defined above, yet some actors engage in violent activities abroad. The locations of conflict are on average at a distance of 551km to the capital, in contrast the signatory groups are closer by about 50km.[18]

Looking at the network of direct non-civilian allies and enemies in combat, Table 1.1 Panel B, an actor has 0.95 allies and 16.15 enemies (with a median of 9), respectively, whereas signatory groups have about 40% more allies and enemies.

The natural resource endowment at the grid-cells included in the analysis is scarce on average, with a presence of precious metal (e.g. diamond, cobalt, copper, gold, silver) at 1 to 3% of the observations, slightly higher for oil and gas at 5 and 4% respectively on average (Table 1.1 Panel C). The signatory groups are active in locations that are less endowed compared to the non-signatory, less populated and as well with a slightly higher temperature, less rainfall, yet higher values of Normalised Difference Vegetation Index (NDVI).

Lastly turning to the peace agreements, the baseline sample contains 234 different treaties, of which 86% classified as *Intra* addressing a conflict within a country (state vs. non-state actor), and the remaining as *Local*, a response to a local conflict without the direct involvement of the government (non-state vs. non-state actor). On average the agreements have 5.5 signatories based on the original PAX dataset and 4.5 based

[17] The overall direct fatality count for the whole sample period is reported at 165937 deaths. These fatalities are to a large degree caused in events of violence against civilians, and they are unaccounted for deaths due indirect reasons such as to spread of diseases, psychological damage etc.

[18] To account for the size of the country the measure is standardised by the largest distance between two points of the country border (diameter). Similarly, the measure has a sample mean of 0.44, with signatory groups being 0.03 units closer to the capital.

Table 1.1: Descriptive statistics

Variable name (i)	Sample mean (ii)	Std. dev. (iii)	Median (iv)	PA vs. Not PA (v)	Std. err. (vi)	N (vii)
Panel A: Conflict events						
Lifespan of actor (y)	11.49	7.51	8.83	4.61***	0.02	403334
Time active before Agt (m)	16.24	9.14	17	4.58***	0.03	403334
Conflict Event	0.07	0.25	0	0.01***	0	403334
Conflict N Events	0.14	0.95	0	0.04***	0	403334
Fatalities	0.97	91.85	0	0.39**	0.17	403334
Event abroad	0	0.07	0	0***	0	403334
Event battles	0.04	0.2	0	0***	0	403334
Event V.ag.Civi	0.02	0.15	0	0***	0	403334
Distance capital (km)	550.79	435.09	446.78	-48.46***	1.31	403334
Distance capital (std km)	0.44	0.57	0.36	-0.03***	0	403334
Actor density per grid-cell (n/km2)	0	0	0	0***	0	403334
Panel B: Conflict network						
Number of allies	0.95	1.71	0	1.55***	0.01	403334
Number of enemies	16.15	19.36	9	19.17***	0.07	403334
Number of signatory allies	0.17	0.57	0	0.25***	0	403334
Number of signatory enemies	2.33	2.93	1	3.32***	0.01	403334
Panel C: Geographic variables						
Pop Density 2015	141.31	361.39	32.57	-33.94***	1.26	403119
Pop Density 2000	93.4	249.37	21.46	-22.74***	0.84	403119
Elevation (m)	647.38	511.03	485.34	-3.35***	1.29	403334
Diamond, 0/1	0.03	0.17	0	0	0	403334
Cobalt, 0/1	0.01	0.08	0	0***	0	403334
Copper, 0/1	0.03	0.17	0	-0.01***	0	403334
Gold, 0/1	0.03	0.18	0	0***	0	403334
Iron, 0/1	0.03	0.17	0	-0.01***	0	403334
Lead, 0/1	0.01	0.11	0	-0.01***	0	403334
Silver, 0/1	0.01	0.12	0	0***	0	403334
Zinc, 0/1	0.01	0.12	0	-0.01***	0	403334
Minerals Top7, 0/1	0.08	0.27	0	-0.02***	0	403334
Oil, 0/1	0.05	0.21	0	-0.02***	0	403334
Gas, 0/1	0.04	0.2	0	-0.02***	0	403334
Panel D: Climate variables						
NDVI	4252.3	2215.56	4103.33	103.89***	5.35	347442
Precipitation (mm)	2.77	3.56	1.25	-0.11***	0.01	403334
Temperature (C)	25	4.36	25.46	0.16***	0.01	403334

Notes: Descriptive statistics at the non-state military actor level, including activities within two years before and after the signing of a peace agreement in the home-country. The resolution of grid-cells measures 0.5×0.5 arc degrees. Columns v and vi compare signatory groups to non-signatory groups, where differences are calculated by regressing each variable on an indicator equal to 1 if the group signed a peace agreement, controlling for actor time trend, month and country fixed effects, including robust standard errors in column vi, where *, **, and *** indicate significance at the 10%, 5%, and 1% levels.

on the ACLED matched actors. The government is directly a co-signatory in 72% of the agreements.

At large, the actors' characteristics are majorly significantly different comparing signatory to non-signatory (column v in Table 1.1), suggesting that on average across the full sample (ex ante and ex post of the signature) they are fundamentally different. Details about the variables and their data sources are provided in the Appendix section A.

1.4 Measuring armed group behaviour

This section discusses the empirical analysis. Based on a panel event-study design, I describe the measurement of violent activity by signatory non-state military actors around the timing of the first and last peace agreement signature. To understand whether the treaties are associated with changes in violent behaviour, the resulting event study coefficients are tested against a trend break in a second step.

1.4.1 Empirical strategy

The study exploits time variation in peace treaty signature across actors within grid-cells using a panel event study design of the following specification:

$$y_{ict} = \alpha + \sum_{\tau} \sigma_t \mathbf{D}_{\tau,ict} + \mu_i + \gamma_c + \eta_t + \beta \mathbf{X}_{ct} + \varepsilon_{ict} \tag{1.1}$$

where, y_{ict} is the outcome of interest (conflict prevalence or intensity) of actor i in grid-cell c in month t. The actor and grid-cell fixed effects, μ_i and γ_c, account for unobservable time-invariant determinants of violence across actors and grid-cells such as geography, natural resource endowments or ethnicity. The inclusion of time fixed effects η_t, non-parametrically adjusts for nation or region wide trends in violence. X_{ict} is a vector of time-varying actor and grid-cell controls, and ε_{ict} is the error term allowed to be heteroskedastic.

The vector $\mathbf{D}_{\tau,ict}$ is composed of separate indicator variables for the months before and after a peace agreement is signed by the parties, where τ is normalised to zero in the month of signing, indicating the end of the negotiation phase. The months included range from 24 months before and after the signing, $\tau \in (-24, 24)$. The never treated actors (non-signatory) are included in a robustness check, in which case their τ is set to missing. The corresponding subscript c of the σ coefficient serves different selection specifications based on grid-cell activity.

Each actor's first and last peace agreement is evaluated separately and not conditioned on other actors' signing within the considered time frame in spatial proximity. To account for correlation in unobservables that influence actors' violent behaviour operating in proximity, standard errors are clustered at the grid-cell level attenuating spatial autocorrelation. The inclusion of never treated non-state military actors, that are an unlikely sound counterfactual, yet grid-cell fixed effect and actor-variable controls increase their comparability. These observations can be used to estimate the month and grid-cell effects independently of the effect of the peace agreement and hence aid the estimation.

All specifications control for non-state military actor density per month per grid-cell, precipitation, temperature and the normalised vegetation index. These determinants are found to be sources of variation in likelihood of conflict prevalence at the grid-cell level, (e.g. see Harari and La Ferrara, 2018). Furthermore, the following time-varying characteristics at the actor level are included: size (measured as average area covered over rolling time window of two years), the cumulative number of allies and enemies in combat and age (measured in years since first observation). This implies that conditional on individual characteristics (time constant and selected time-varying ones) and grid-cell dynamics the individual conflict behaviour observed is interpreted as a consequence of peace agreement dynamics.

The coefficient of interest is $\hat{\sigma}_\tau$, which estimates average monthly violence, prevalence and intensity, in the time before and after a group's signing of the first or last agreement.

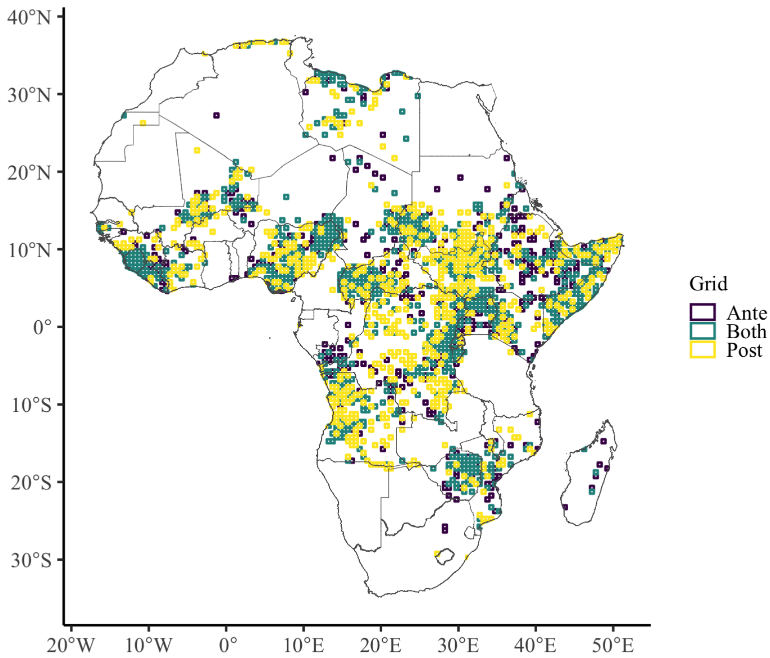
Using grid-cells as a unit of analysis ensures that the definition of location is not endogenous to conflict events as it is fixed in space and time, this in contrast to using politically defined units. In addition, aggregating conflict event locations within grid-cells addresses potential measurement error in geo-locating the event, and its subnational character ensures that the observed association is driven more by local characteristics than by global (country or regional-level) ones.[19] Controlling for unobservable time-invariant characteristics at the grid-cell level, I address the concern that the analysis might reflect aspects of local geography, history, institutions or culture.

To account for non-state actor mobility within and cross country across time, the study selects based on time and location. The baseline sample focuses on grid-cells where the actor was active in within the two years time window before and after the signature. For the event study dynamics this implies that grid-cells are included for the ex ante months where the actor was not active and vice versa for the ex post period. It accounts for the locations that are within reach of an actor within two years of the signature

[19] The spatial resolution rests on a 0.5×0.5 arc degree is in line with the majority of studies looking at all or a subset of countries in Africa, see, e.g. Besley and Reynal-Querol (2014); Berman et al. (2017); Harari and La Ferrara (2018), though, it will be interesting to explore differential grid-cell resolutions and their impact on the result.

date, the time of concluding the treaty. In two separate specifications locations are selected either on activity ex ante or ex post, acknowledging the fact that actors might move away from or towards to a location over time. For the baseline specification this results in 2298 grid-cells included, 1799 and 1864 for ex ante and ex post respective. Figures 1.2 and 1.3 illustrate the grid-cell selection for the first and last agreement, respectively. Comparing the first to the last agreement one can observe an aligned spatial movement, where ex post grid-cell in the first agreement likely lie close to ex ante grid-cell in the last agreement.

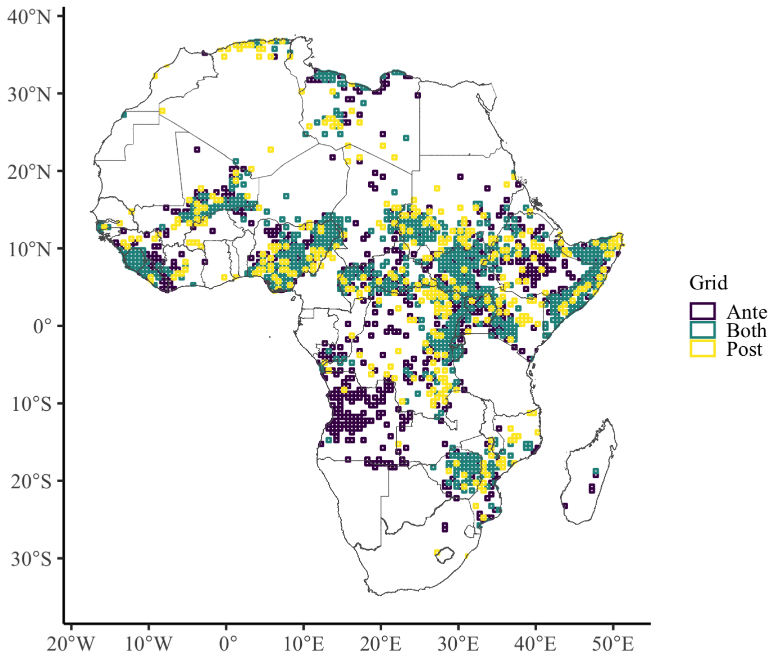
Figure 1.2: Grid-cell type according to actor activity time (1st agreement)



Notes: This map illustrates the spatial distribution of grid-cell presence based on actor activity, in the case of the first agreement.

The key assumption for identification of the policy effect in event studies, σ_τ in Equation 1.1, is absence of pre-trends. As outlined in Section 1.2 and illustrated in Figures C1 and C2 for the first and last agreement respectively, the context studied shows large upward trends in violence, indicative that the peace negotiation and agreed upon deal are not strictly exogenous. A concern is that more violent non-state military actors are more likely to sign a peace agreement due to unobserved individual and local socio-economic conflict dynamics or interventions from third parties (mediators, international pressure). The dynamics of negotiation beyond observed conflict events by negotiating parties remain largely unobserved, similarly to what degree the agreed upon deal addresses the local grievances, solves the disagreements at stake. These unobservable characteristics might yet be relevant in explaining observed conflict dy-

Figure 1.3: Grid-cell type according to actor activity time (last agreement)



Notes: This map illustrates the spatial distribution of grid-cell presence based on actor activity, in the case of the last agreement.

namics. They are partially addressed by distinguishing the type of peace agreement signed allowing for a more comparable subset of dynamics across actors and countries.

Of further concern might be that non-state signatory actors are not comparable by design of signatory status apart from general characteristics of group organisation and civil conflict engagement. Including actor level controls accounts for obvious disparities, yet it is more often the case that critical information is missing for military actors. Among such factors are, better negotiation skills over time due to a learning effect across multiple peace agreements, information about the likelihood of commitment to obey the agreement terms by co-signatories or willingness to negotiate and reach a deal. The study addresses these sources of skill and information bias by limiting the analysis to the signature of the first agreement, as well as by including size and age controls. Furthermore, grid-cell fixed effects account for local/national differences in eligibility criteria to participate in peace negotiations.

In light of the pre-trends, I formally examine in a second step whether the conclusion of a peace agreement is associated with a reduction in violence by testing a mean shift model. Following Greenstone and Hanna (2014) I estimate the following equation:

$$\hat{\sigma}_\tau = \pi_0 + \pi_1 1(Agreement)_\tau + \pi_2\tau + \pi_3(1(Agreement)_\tau \times \tau) + \varepsilon_\tau \qquad (1.2)$$

where $\tau \in (-24, 24)$, the term $1(Agreement)_\tau$ is an indicator variable for whether the actor has concluded the negotiation stage and signed the agreement , $\pi_2\tau$ controls for a linear time trend in event time to adjust for pre-trends in signatory actors, the interaction term between $1(Agreement)_\tau \times \tau$ incorporates the fact that agreements are implemented over a longer time horizon, where the full impact may emerge only over time. The dependent variable $\hat{\sigma}_\tau$ is the resulting coefficient from Equation 1.1 measuring average monthly violence for the 24 months before and after a group's signing.

This difference-in-difference approach allows to test for a trend break comparing ex post to ex ante while it accommodates the differential trends across non-state signatory actors. The coefficient of interest, π_1, indicates the policy effect of the peace agreement signature, comparing the implementation phase (post) to no agreement/negotiation phase (ante).[20]

Lastly, a note on the trade-off of using a monthly frequency. It represents a drawback as a larger level of noise is allowed in the information as conflict events can be rare, yet, non-state military actors are agile and temporal aggregation may trade for valuable information.

1.5 Results

In the following I will discuss the results. First, event study graphs illustrate conflict dynamics at the extensive and intensive margin around the timing of the peace agreement signature. Second, the impact of the policy tool is estimated testing for trend breaks in a difference-in-difference style design. These results combined are interpreted to be indicative of the impact of peace processes on signatory non-state military actors during negotiation and after concluding a deal.

1.5.1 Conflict prevalence and intensity

The event study graphs in Figure 1.4 plot the estimated σ_τ based on Equation 1.1 against the monthly time frame of two years around the signing. They depict the impact associated with concluding the first peace agreement on conflict prevalence (first column) and conflict intensity measured as logarithm of the number of conflict events

[20] The start of implementation is not necessarily immediately after the signing, or at least not for all provisions, as discussed in Section 1.2, rather the post signature phase is interpreted as the process of implementation post agreement on the terms.

(second column) across different grid-cell selections; Panel A employs the baseline selection including all grid-cells where the actors have been active in during the two years before and after the signing, Panel B includes the grid-cells selected on activity before and Panel C after the signing, respectively. The vertical dotted line demarcates the month of signing the agreement, $\tau = 0$, while the horizontal line refers to the normalised outcome variable to be equal to zero in the month of signing $\tau = 0$. Point estimates are reported with confidence bands at the 95% level of significance.

Across the three specifications the signatory groups show a worsening trend in terms of violence (prevalence and intensity) ahead of signing, in particular during the last six months.[21] Point estimates suggest that violence, prevalence and intensity, more than doubles compared to the month of peace agreement signature, predominantly in locations where fighting is active before the signing.

Comparing Panel B to Panel C in Figure 1.4 that are distinctive in terms of dominant conflict location before and after, the significant reduction observed in the former and its absence in the latter suggests that movements away from ex ante locations of conflict explain the differences in the illustrated effect.

Considering the Figure 1.4 with respect to the impact of concluding the negotiation with an agreement and its consequent period of implementation, the point estimates depict that the signature was effective in reversing the upward trend in violence measured at the extensive and intensive margin.

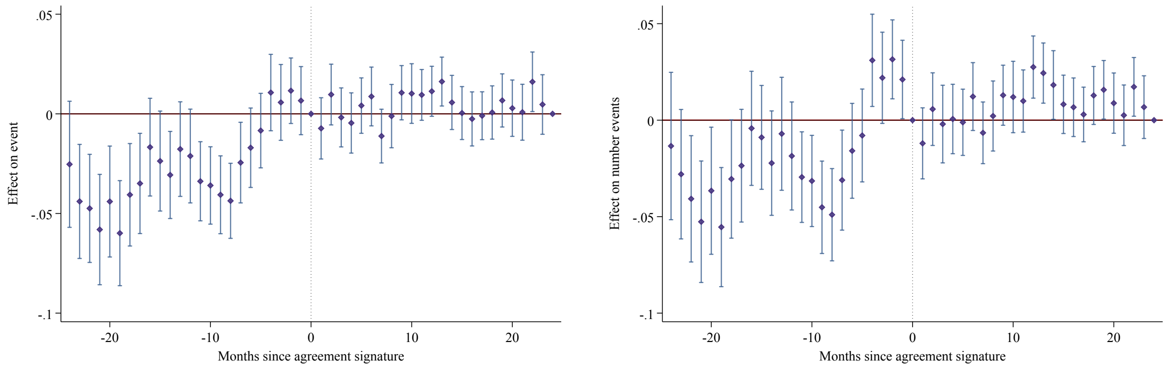
To test whether violence dynamics are subject to a mean shift of negative sign, Table 1.2 reports the key coefficients from fitting Equation 1.2. The estimated breaks largely confirm the visual impression from the respective event study graphs. The estimate for the full sample in column (i) is negative and of small magnitude, providing little evidence that the peace agreement had an impact in the month of signing. Considering the subsample of locations that hosted signatory groups before the signing (ante grid-cells) conflict prevalence reduces by 0.051 in the month of signing, and by 0.069 six months thereafter ($\pi_1 + 6\pi_3$). This suggested decline is large, representing a drop of 38%, respectively 53%, compared to the ex ante mean of conflict prevalence. This in turn is reflecting the increases in violence observed ahead of signing (Figure 1.4). Similarly for conflict intensity measured in logs of number of events or fatalities, while the full sample shows a weak policy effect, the locations affected by violence before the treaty was concluded observe a comparable reduction in the month of signing compared to the control mean, of 31% and 40% in log number of events and fatalities

[21] Note, although the graphs illustrate upward trends ex ante, and as such trends that differ in signatory groups, they do not depict a mean reverting process, as similar downward trends are non-identifiable.

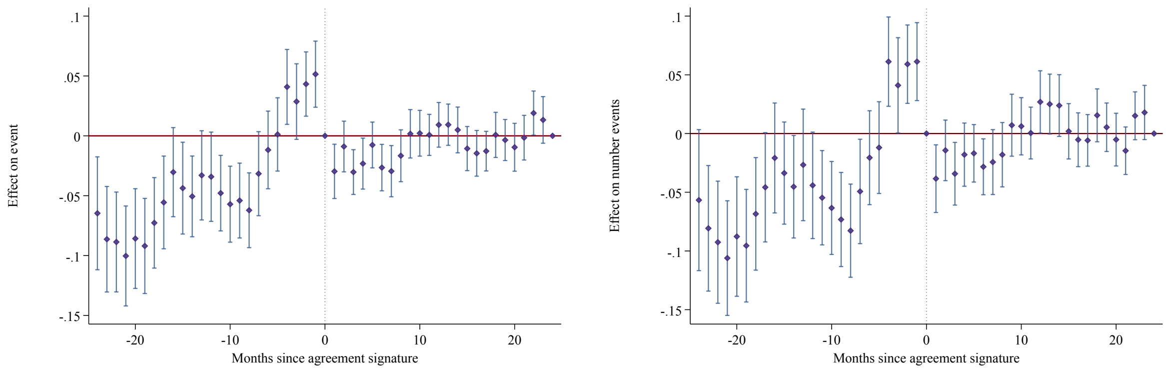
respectively, (columns v, viii).

Figure 1.4: Event study peace agreement on violence (1st agreement)

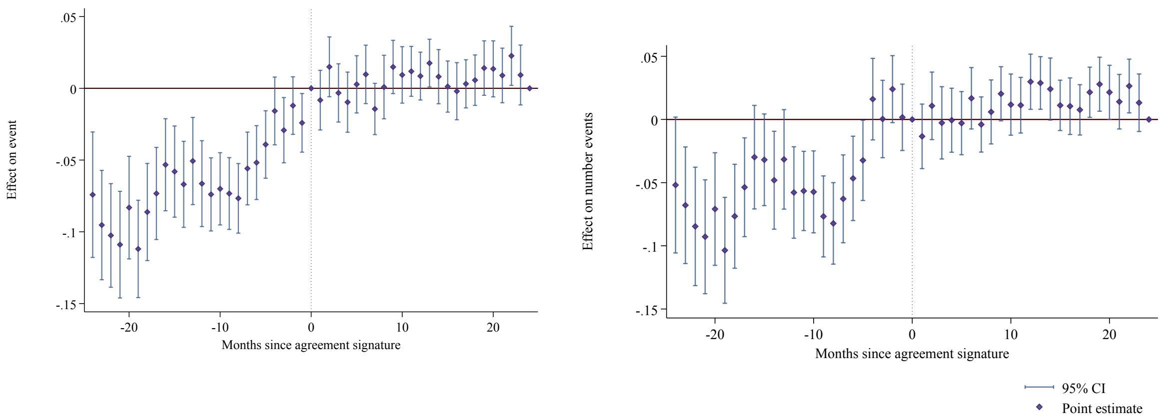
(a) Panel: full grid-cells



(b) Panel: ante grid-cells



(c) Panel: post grid-cells



Notes: Event study graphs depicting the dynamics 24 months before and after the peace agreement signature on outcomes of conflict prevalence (left) and conflict intensity measured in number of events (right).

As robustness check, I include the active non-state military actors that are not signatory during the sample period (never treated) at times of signing in their country of origin, see corresponding event study graphs in Figure D1. The precision of the point estimates has increased, and the pre-trend dynamics are similar but of larger magnitude, with conflict prevalence being reduced by 87% in the month of signing compared to the control mean (column ii in Table D1, reflecting the increase ahead of signing.

In contrast, the dynamics illustrated based on signing the last agreement in Figure B2. The positive upward trend ahead of signing remains visible based on the point estimates, though less precisely estimated. The policy coefficients in Table B1 indicate that the peace agreement signature is associated with a reduction in conflict prevalence and intensity, by magnitudes of 46 to 51% across the three grid-selections (columns i, ii, iii). Note, that the subsample of last agreements shows a clear overall reduction in all cells, actor's mobility is not seen to be a driver here. The effect six months after the signing measures a reduction of 46% in locations that are mainly exposed to conflict by the recent signatory groups after the signing. This suggests, that actors use violence after the first but less so after the last agreement, independent of locations.

Table 1.2: Trend breaks estimates of peace agreements' effect on violence (1st agreement)

	Event			Number of events			Number of fatalities		
	(i)	(ii)	(iii)	(iv)	(v)	(vi)	(vii)	(viii)	(ix)
π_1	-0.007	-0.051***	0.006	-0.007	-0.045***	0.003	-0.001	-0.046***	0.013
	(0.006)	(0.012)	(0.007)	(0.009)	(0.016)	(0.011)	(0.011)	(0.016)	(0.017)
π_2	0.003***	0.005***	0.004***	0.002***	0.005***	0.004***	0.001	0.003***	0.001
	(0.000)	(0.001)	(0.000)	(0.000)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
π_3	-0.002***	-0.003***	-0.004***	-0.002***	-0.003***	-0.003***	-0.002**	-0.003**	-0.003**
	(0.000)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
N	47	47	47	47	47	47	47	47	47
Control-mean ante	0.077	0.131	0.075	0.085	0.144	0.088	0.068	0.116	0.067
Grid-cell selection	full	ante	post	full	ante	post	full	ante	post

Robust standard errors are reported in parentheses, *, **, and *** indicate significance at the 10%, 5%, and 1% levels.

1.5.2 Peace agreement type

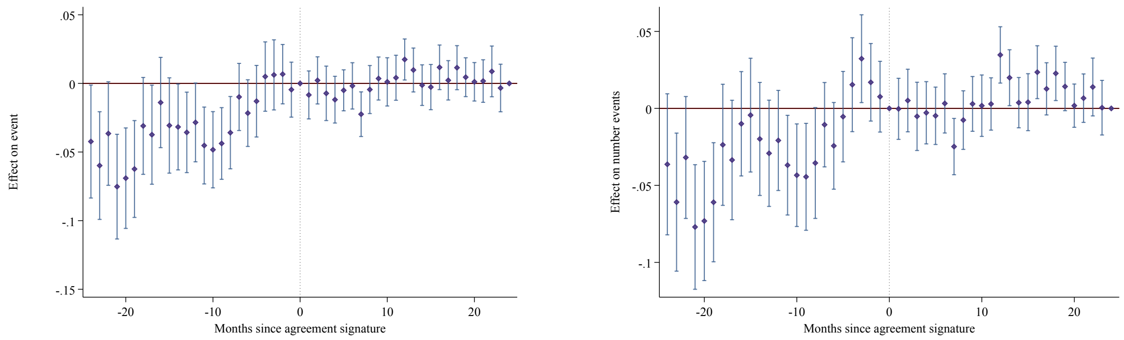
The type of peace agreement chosen by the signatory actors is directly linked to ex ante conflict dynamics, thus comparison across types is difficult.

Figures 1.5 and 1.6 show the event study plots for four distinctive peace agreement types of the first signature per actor. Across types the graphs show stabilisation of violence unchanged or lower than the month of signing. This is largely verified by the point estimates in Table 1.3. The two agreement types that include extensive negotiation periods, where the party discuss and agree on substantive issues show almost no upward trend in violence ahead of signing and a clear and substantive drop thereafter

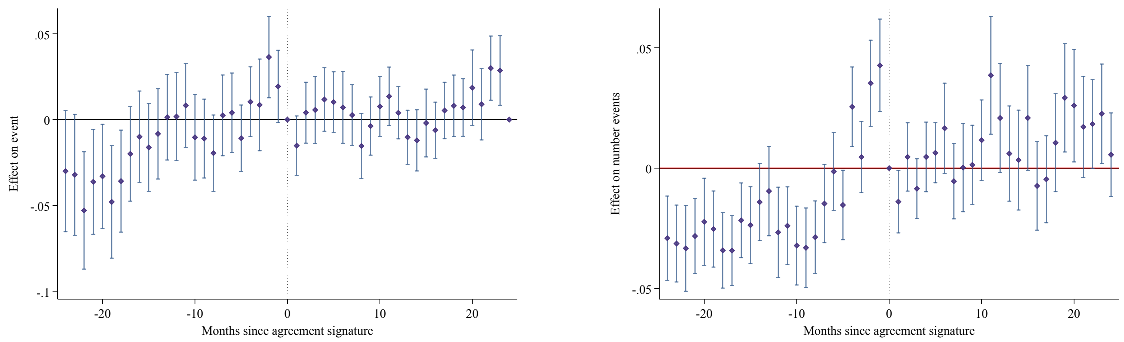
(Figure 1.6). The level of comprehensiveness in substantive framework type of agreements are positively associated with a reduction in violence of 31 to 63% in conflict prevalence and 50 to 258% in conflict intensity (columns v, vii and vi, viii respectively in Table 1.3). This finding would plausibly support one line of argumentation in the literature that more substantial provisions, like political power sharing reduce the risk of renewed conflict, (e.g. Joshi et al., 2017; Cederman et al., 2015) Yet, the findings do not withhold the stricter specifications when including never takers (Figure D2 and Table D2). This discussion is further substantiated by the last agreement signature where no distinctive impacts are associated with the substantive frameworks but rather with the ceasefire and pre-negotiation framework (Figure B3, Table B2). It suggests instead that last agreement signature is associated with a conflict reduction of similar magnitude at 31% for both, conflict prevalence and intensity (columns i, ii).

Figure 1.5: Event study peace agreement on violence by treaty type (1st agreement)

(a) Panel: Ceasefires



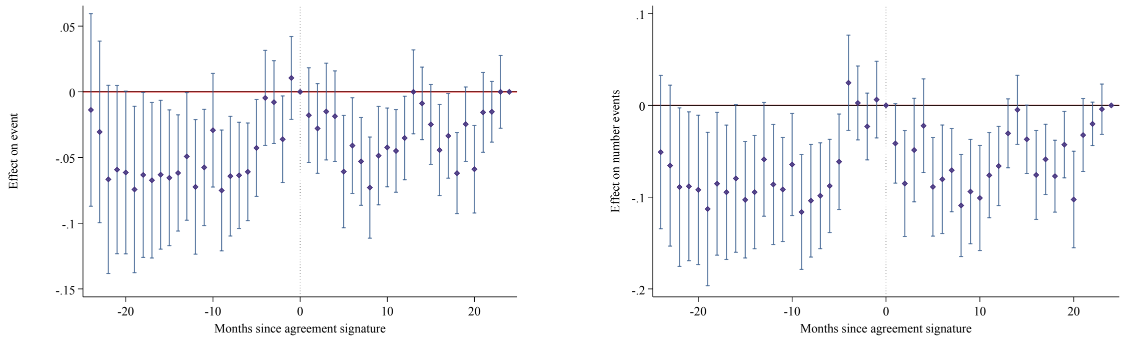
(b) Panel: Pre-negotiation



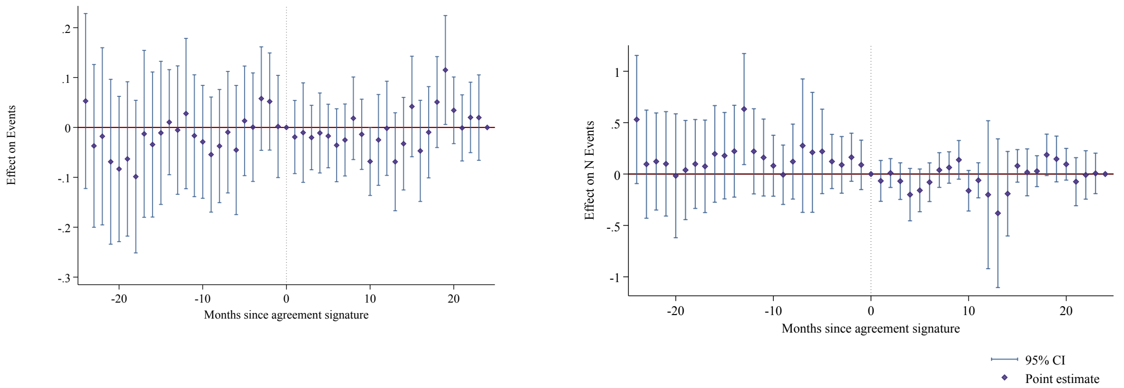
Notes: Event study graphs depicting the dynamics 24 months before and after the peace agreement signature on outcomes of conflict prevalence (left) and conflict intensity measured in number of events (right).

Figure 1.6: Event study peace agreement on violence by treaty type (1st agreement)

(a) Panel: Substantive framework, partial



(b) Panel: Substantive framework, comprehensive



Notes: Event study graphs depicting the dynamics 24 months before and after the peace agreement signature on outcomes of conflict prevalence (left) and conflict intensity measured in number of events (right).

Table 1.3: Trend breaks estimates of peace agreements by type (1st agreement)

	Ceasefire		Pre-neg		SF part		SF comp	
	Event (i)	N Event (ii)	Event (iii)	N Event (iv)	Event (v)	N Event (vi)	Event (vii)	N Event (viii)
π_1	-0.011	-0.017*	-0.019**	-0.024**	-0.029**	-0.053***	-0.042*	-0.178*
	(0.007)	(0.010)	(0.008)	(0.009)	(0.011)	(0.019)	(0.025)	(0.099)
π_2	0.003***	0.003***	0.002***	0.003***	0.002***	0.003***	0.003**	-0.002
	(0.000)	(0.000)	(0.000)	(0.000)	(0.001)	(0.001)	(0.001)	(0.005)
π_3	-0.002***	-0.002***	-0.002***	-0.002***	-0.001	-0.001	-0.002	0.001
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.002)	(0.007)
N	47	47	47	47	47	47	47	47
Control-mean ante	0.097	0.112	0.053	0.051	0.094	0.107	0.067	0.069
Grid-cell selection	full	full	full	full	full	full	full	full

Robust standard errors are reported in parentheses, *, **, and *** indicate significance at the 10%, 5%, and 1% levels.

1.6 Conclusion

Using a novel dataset that matches conflict events and peace agreements at the actor level, this paper examines the association between peace agreement and signatory actors and its dynamics during negotiation and implementation phase. I find that signatures of peace agreements representing the formal end to a negotiation process are associated with observed reductions in conflict prevalence and intensity, measured as log number of events and log number of fatalities, where the estimates are less precise for the latter.

Comparing descriptive and quantitative evidence from grid-cells hosting signatory actors prior to the signing to predominantly newer locations of activity ex post, I find that violence in the former is associated with a reduction of 38% in the month of signing, respectively 53% six months thereafter. In contrast, there is no comparable change in signatory behaviour estimated for newer locations. These findings are robust when including pure control groups in the regression. This suggests that signatory groups relocate to new places post signing.

Considering instead the last agreement signed per actor, the results indicate an overall reduction in violence independent of location. As of the sample considered the first agreement on average is followed by further agreements, suggesting that the first agreement did not address and solve the issue at stake entirely. These insufficient agreements and implementations might be descriptively characterised to be associated with levels of violence that are comparable or higher than before signing, yet they the deal conclusion effectively halts the upward trend.

The study does not allow the disentanglement of the mechanisms for whether high violence increases the likelihood of a peace agreement from whether armed groups strategically use violence ahead of the signing to attempt to join or carve out a better position in the negotiations. In absence of exogenous variation in peace agreements, with an extensive set of individual armed group's and grid-cell characteristics, I document dynamics of non-state signatory actors' behaviour at times of peace agreement negotiations, conclusions and initial implementations.

Understanding the role of peace negotiations and signed deals is important, not only for predicting outcomes, but also for designing and implementing policies to reduce and manage the risk of conflict and to shorten the duration of existing conflicts. To this end this paper can be considered to be the first step towards a better understanding of the causal effect of peace agreement on violence. However, more fine grained data on the timing of negotiations, to what degree the peace agreement addresses the original grievances of the actors and details on the implementation would allow to disentangle the current trends into mechanisms of strategic actor behaviour.

APPENDIX

This Supplementary Material appendix provides greater detail on data sources, variables and methods used in this chapter (Appendix Section A), and summarizes findings from additional analyses (Appendix Section B).

A Data and methodological procedures

A.1 Variables and data sources

The following table presents a description of the variables used in this chapter.

Variable (Source)	Description
Administrative divisions (GADM)	Calculated as the largest area covered by the intersection of national boundaries' polygons and the grid-cells. The data is from GADM version 3.6, released in 2018, which can be accessed at [https://gadm.org]. The boundaries for Sudan before the independence of South Sudan in 2011, are constructed by the author as the joint areas of the two countries. Western Sahara is defined as a separate polygon by GADM and considered as such in the analysis.
Capital cities (CShapes)	Calculated as the presence of a capital city in each grid-cell. The capital is largely defined as the current (2019) *de jure* capital that hosts the executive government of the country, it is not necessarily the economic centre of a country. The location and the definition of the national capital city is from The CShapes 2.0 Dataset (Schvitz et al. 2021). For the territory of Western Sahara, the capital city is defined as Rabat, see *Administrative divisions*.
Diamonds (PRIO)	Measured as the binary occurrence of any known diamond deposits in each grid-cell. Occurrence is defined as any "activity, meaning production (either commercial or artisan) or confirmed discovery". Data are from Diamond Resources, PRIO, (Gilmore et al. 2005).
Distance to capital (author's calculation)	Shortest distance (straight line) calculated in kilometres from the centroid of each grid-cell to the national capital. This measures does not account for the distance to foreign capitals, that might impact the conflict and peace dynamics. Data on the national capital, see *Capital*.
Homeland area (author's calculation)	The land area under likely influence by each armed group calculated in square kilometres over the maximum extent of area covered over a lifetime within the home-country.
Mineral Resources (USGS)	Measures presence of any gold, silver, copper, iron, lead, cobalt, zinc in each grid-cell separately. The data, from the U.S. Geological Survey Mineral Resources Data System (USGS MRDS), includes location and deposit description globally until 2011. It can be accessed at [https://mrdata.usgs.gov/mrds/].
Petroleum (PRIO)	The presence of all known *oil* and *gas* deposits (active mines and discoveries) are measured separately and conjoint in each grid-cell. The analysis considers on-shore deposits.The data is from Petroleum Dataset, PRIO, version 1.2 (Lujala et al. 2007).
Precipitation (ERA5-Land)	Gridded data at 0.1×0.1 degrees latitude-longitude intersected with the locations of the enumeration areas. Humidity is defined as the accumulated amount of water that has evaporated from the Earth's surface into vapour in the air above, it is measured in meters of water equivalent. The values are coded such that negative values indicate evaporation and positive values indicate condensation. We use the deviations from historical, 30 years, average levels. The data is from ERA5-Land monthly reanalysis dataset, (1981-present) Sabater (2019).

(continued on next page)

Variable (Source)	Description
Population Density (GPWv4)	Calculated as the mean density of population in each grid-cell of the sample. The data, from the Gridded Population of the World Version 4 (GWPv4) models the global human population on 30 arc-second grid-cells based on population census tables and cartography, which can be accessed at [https://doi.org/10.7927/H49C6VHW]. The estimates used are from the year 2020.
Temperature (ERA5-Land)	Gridded data at 0.1×0.1 degrees latitude-longitude intersected with the locations of the enumeration areas. Calculated as deviations from historical, 30 years, averages of temperature levels measured as mean yearly temperature in degrees Celsius. The data is from ERA5-Land monthly reanalysis dataset, (1981-present) Sabater (2019), and converted from kelvin to degrees Celsius by subtracting 273.15.

A.2 Selection of peace agreements

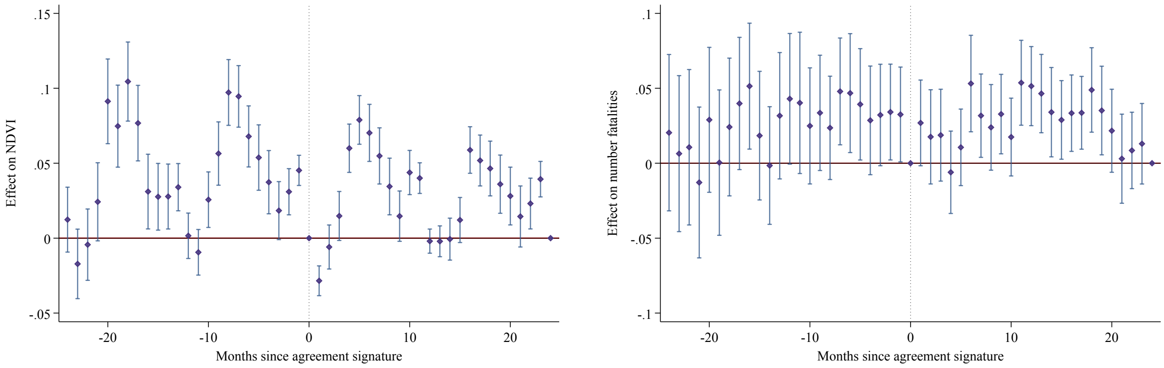
Table A2: List of countries and peace agreements of sample

Country	Date signature	Avg.N.Sig
Angola	1998, 2002, 2006	2
Burundi	1998, 2004, 2009(01,04)	8
Central African Republic	(1997), 1998, 2007, 2008(05,06), 2013(3x!), 2014, 2015, 2016, 2017(10,12), 2018(02,05,08), 2019(01,02)	9.7
Chad	2002, 2003, 2007	2
Côte d'Ivoire	2002, 2003(01,05), 2004, 2005, 2008	3.7
DR Congo	1999, 2001, 2002, 2003, 2006(07, 11), 2008, 2009, 2013(01, 12)	4
Djibouti	2000, 2001	2
Ethiopia	2010(07,10), 2018	2
Guinea	2010, 2016	2.5
Kenya	2008(02,05)	3
Lesotho	2014(10, 12)	7.4
Liberia	2003(06,08)	3
Libya	2015, 2016, 2017(02, 03), 2018(02,04,05,09)	2.7
Madagascar	2009	30
Mali	2006, 2013, 2014(06, 08), 2015, 2018	2.9
Morocco/Western Sahara	2007, 2010	2
Mozambique	2014, 2015	2
Niger	1997, 1998	2.5
Nigeria	2013, 2014, 2016	5
Congo	1999	3.7
Senegal	2004	2
Sierra Leone	1997, 1999, 2001	2
Somalia	1997, 2002, 2006(06, 09), 2008(08,11), 2009, 2010, 2012	3.2
South Sudan	2012, 2014(01, 05), 2016, 2017, 2018(06,07,09)	2.8
Sudan	1997, 1999, 2004, 2005, 2006(01, 06), 2008(06, 11), 2010, 2011(01, 06, 07), 2013, 2017, 2019	2.3
Togo	1999, 2006, 2009	6.3
Uganda	2002(06, 12), 2006, 20078	2
Zimbabwe	2008(07, 09)	3

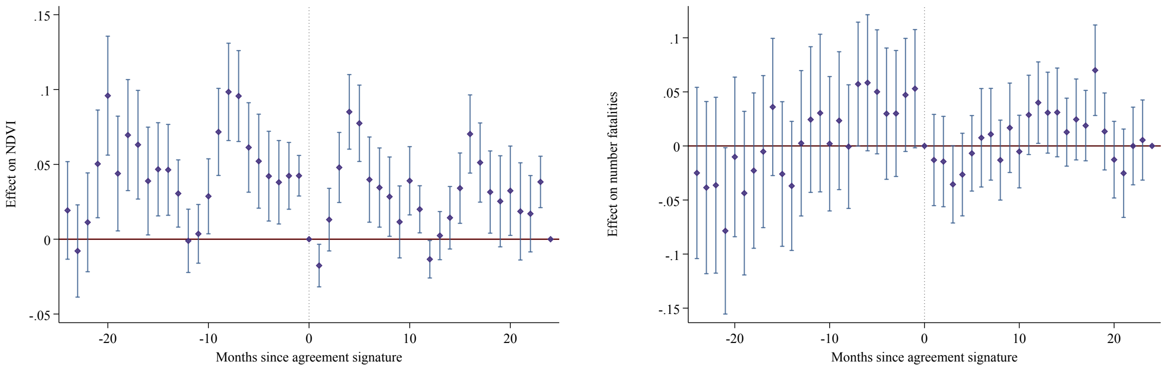
B Supplementary results

Figure B1: Event study peace agreement on NDVI and fatalities (1st agreement)

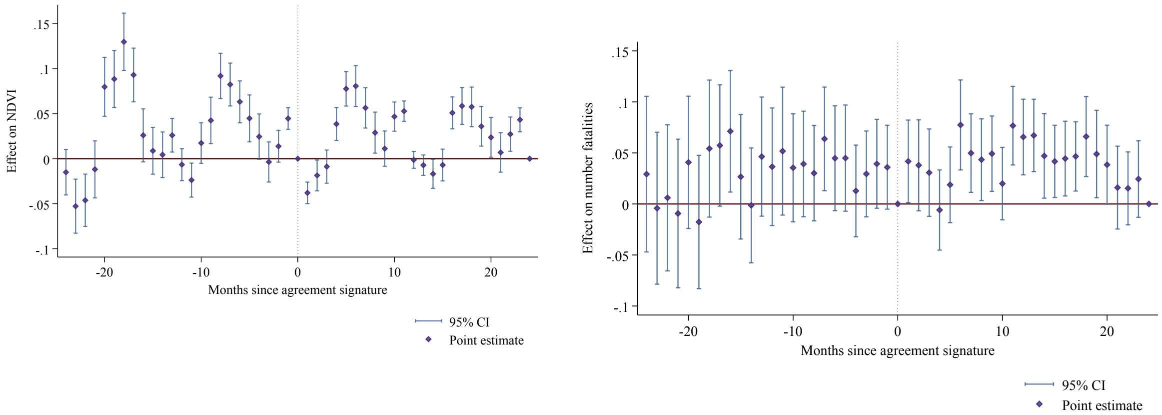
(a) Panel A: full grid-cells



(b) Panel B: ante grid-cells



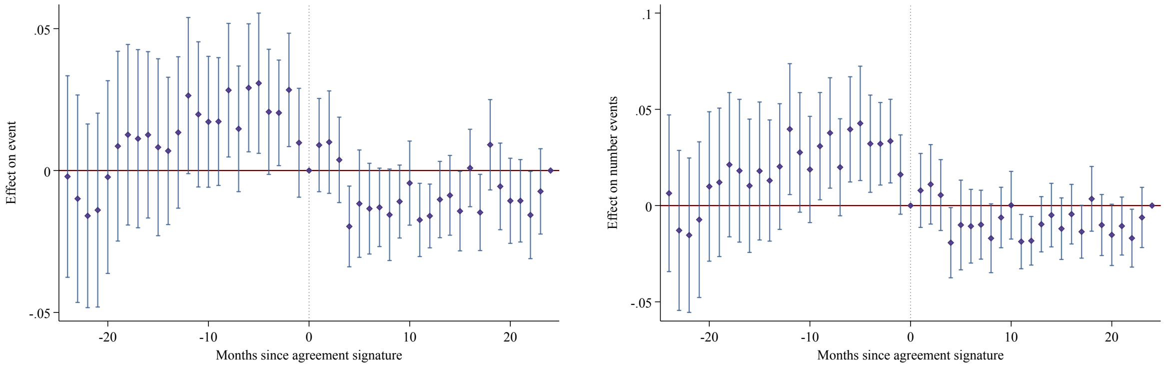
(c) Panel C: post grid-cells



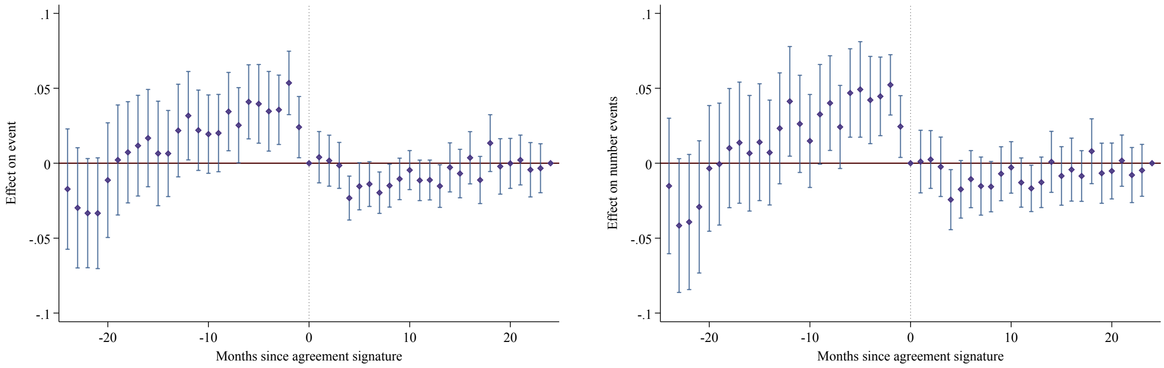
Notes: Event study graphs depicting the dynamics 24 months before and after the peace agreement signature on outcomes of NDVI (left) and conflict intensity measured in fatalities count (right).

Figure B2: Event study peace agreement on violence (last agreement)

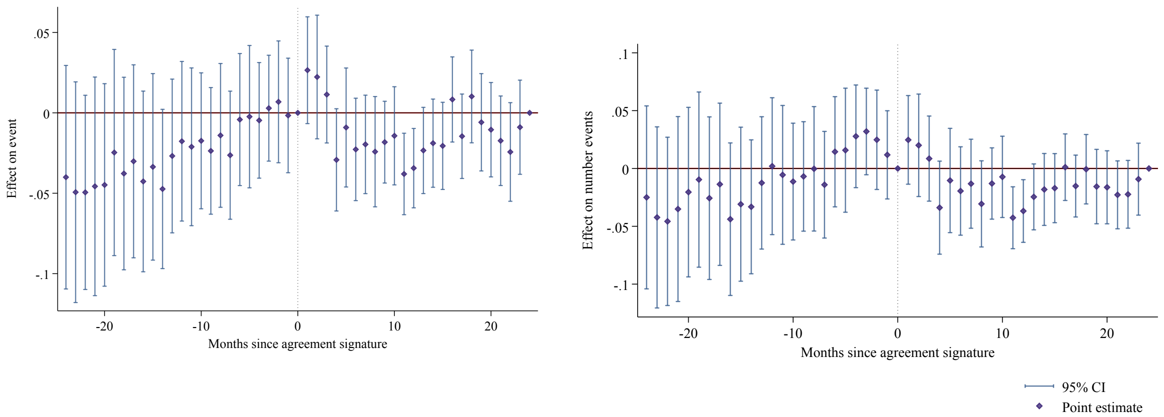
(a) Panel A: full grid-cells



(b) Panel B: ante grid-cells



(c) Panel C: post grid-cells



Notes: Event study graphs depicting the dynamics 24 months before and after the peace agreement signature on outcomes of conflict prevalence (left) and conflict intensity measured in number of events (right).

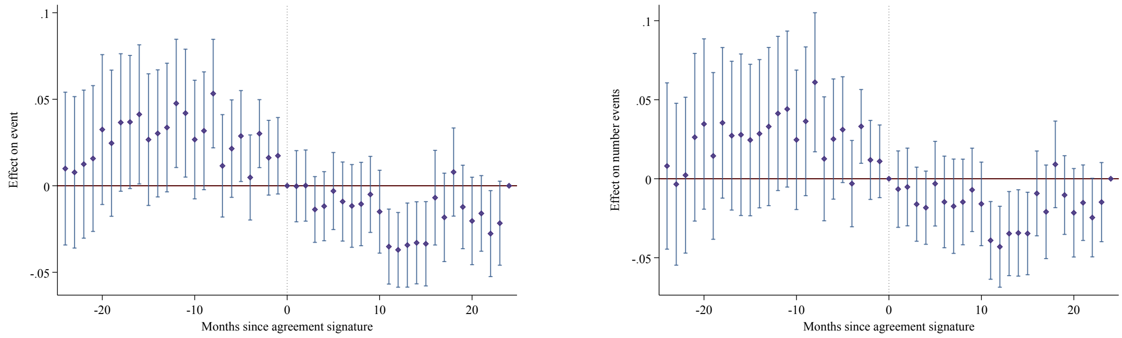
Table B1: Trend breaks estimates of peace agreements' effect on violence (last agreement)

	Event			Number of events			Number of fatalities		
	(i)	(ii)	(iii)	(iv)	(v)	(vi)	(vii)	(viii)	(viii)
π_1	-0.041***	-0.059***	-0.040***	-0.045***	-0.063***	-0.055***	-0.018**	-0.035***	-0.003
	(0.005)	(0.008)	(0.008)	(0.007)	(0.009)	(0.009)	(0.007)	(0.008)	(0.012)
π_2	0.001***	0.002***	0.003***	0.001***	0.002***	0.003***	-0.001***	-0.000	-0.001
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.001)
π_3	-0.001	-0.001	-0.002***	-0.001	-0.001*	-0.002***	-0.001	-0.000	-0.002**
	(0.000)	(0.001)	(0.001)	(0.000)	(0.001)	(0.001)	(0.000)	(0.001)	(0.001)
N	47	47	47	47	47	47	47	47	47
Control-mean ante	0.085	0.114	0.086	0.087	0.098	0.095	0.078	0.105	0.073
Grid-cell selection	full	ante	post	full	ante	post	full	ante	post

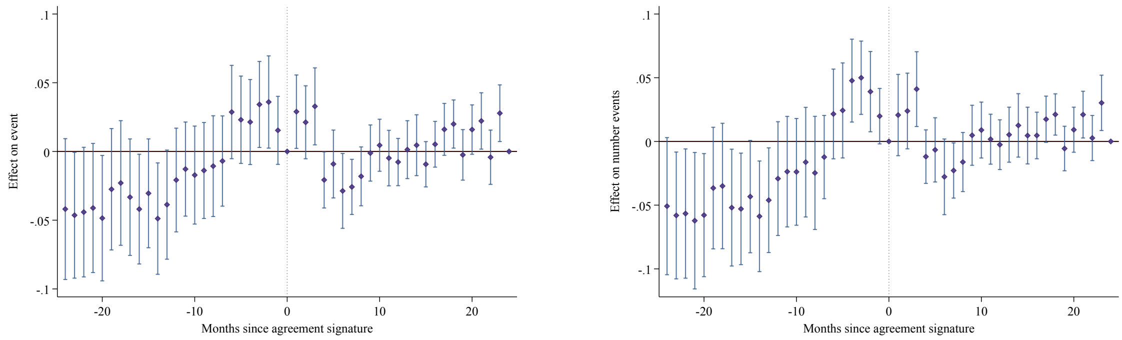
Robust standard errors are reported in parentheses, *, **, and *** indicate significance at the 10%, 5%, and 1% levels.

Figure B3: Event study peace agreement on violence by treaty type (last agreement)

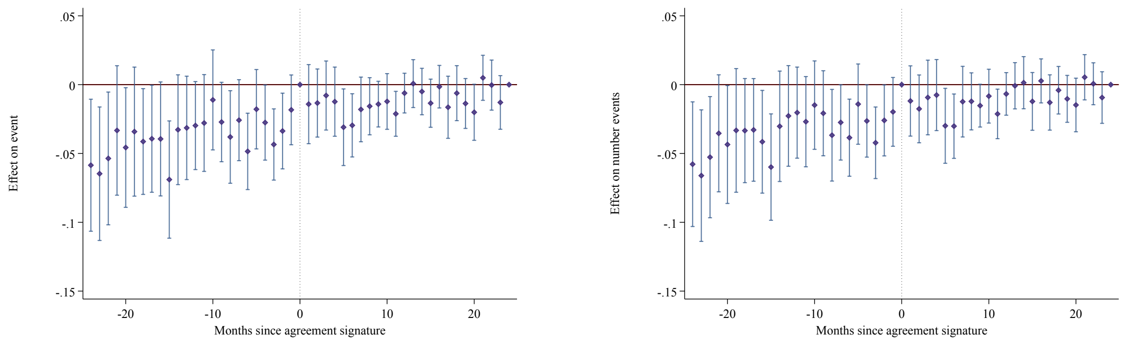
(a) Panel A: Ceasefires



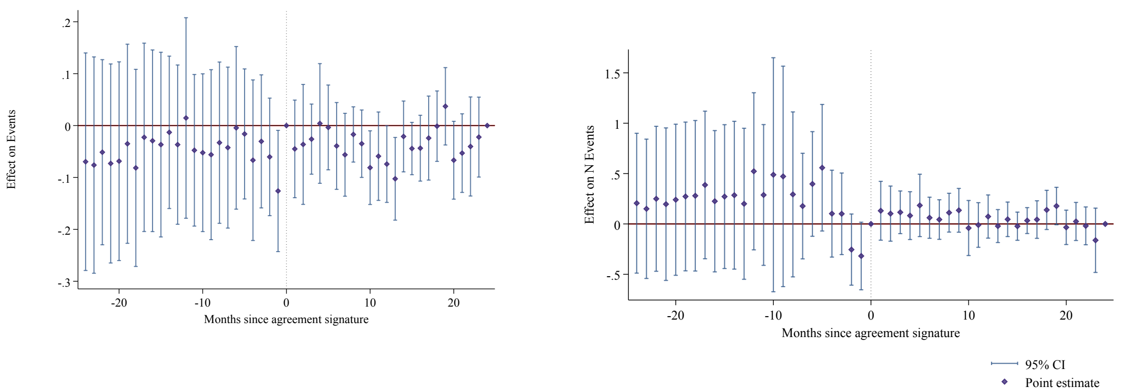
(b) Panel B: Pre-negotiation



(c) Panel C: Substantive framework, partial



(d) Panel D: Substantive framework, comprehensive



Notes: Event study graphs depicting the dynamics 24 months before and after the peace agreement signature on outcomes of conflict prevalence (left) and conflict intensity measured in number of events (right).

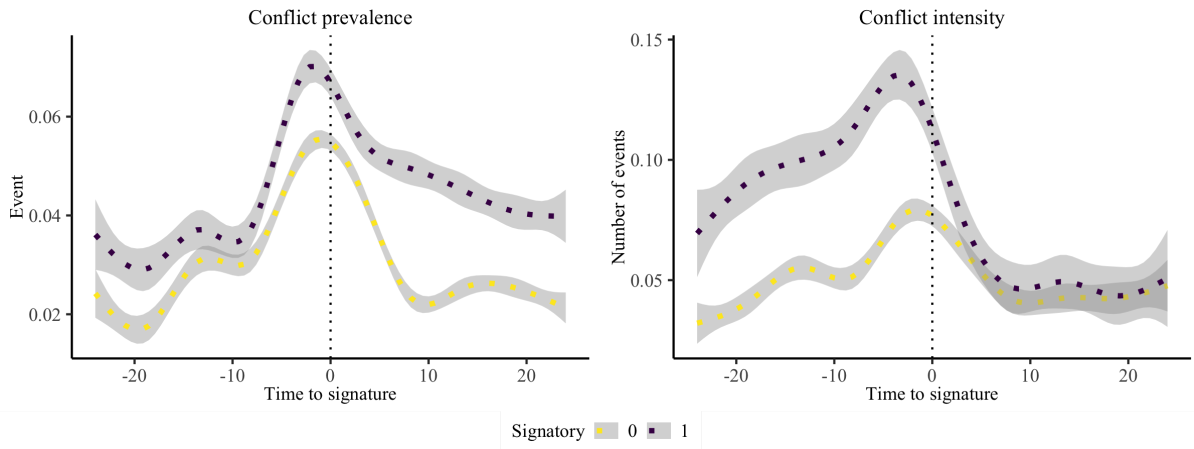
Table B2: Trend breaks estimates of peace agreements by type (last agreement)

	Ceasefire		Pre-neg		SF part		SF comp	
	Event (i)	N Event (ii)	Event (iii)	N Event (iv)	Event (v)	N Event (vi)	Event (vii)	N Event (viii)
π_1	-0.031***	-0.035***	-0.051***	-0.052***	-0.003	-0.002	0.012	0.065
	(0.008)	(0.009)	(0.008)	(0.010)	(0.007)	(0.006)	(0.019)	(0.100)
π_2	-0.001**	-0.001*	0.004***	0.005***	0.001***	0.001***	-0.000	-0.011**
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.001)	(0.005)
π_3	0.001	0.001	-0.002***	-0.003***	-0.000	0.000	-0.000	-0.000
	(0.001)	(0.001)	(0.001)	(0.001)	(0.000)	(0.000)	(0.001)	(0.007)
N	47	47	47	47	47	47	47	47
Control-mean ante	0.097	0.112	0.053	0.051	0.094	0.107	0.067	0.069
Grid-cell selection	full	full	full	full	full	full	full	full

Robust standard errors are reported in parentheses, *, **, and *** indicate significance at the 10%, 5%, and 1% levels.

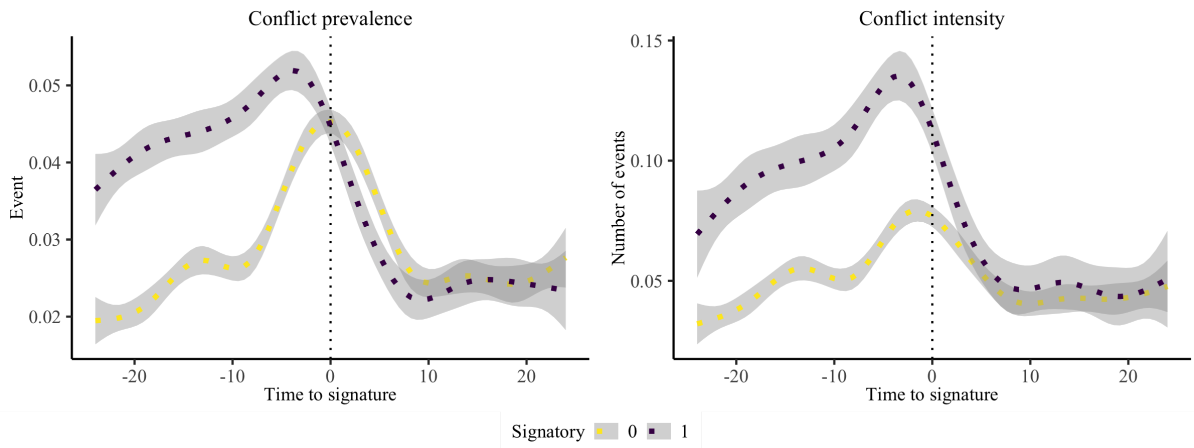
C Additional figures

Figure C1: Conflict prevalence and intensity by signatory status (1st agreement)



Notes: This figure considers the first agreement signed per actor for a scatterplot of conflict events, prevalence (left panel) and intensity (right panel), by signatory status against the time window of 24 months before and 24 months after the signing.

Figure C2: Conflict prevalence and intensity by signatory status (last agreement)

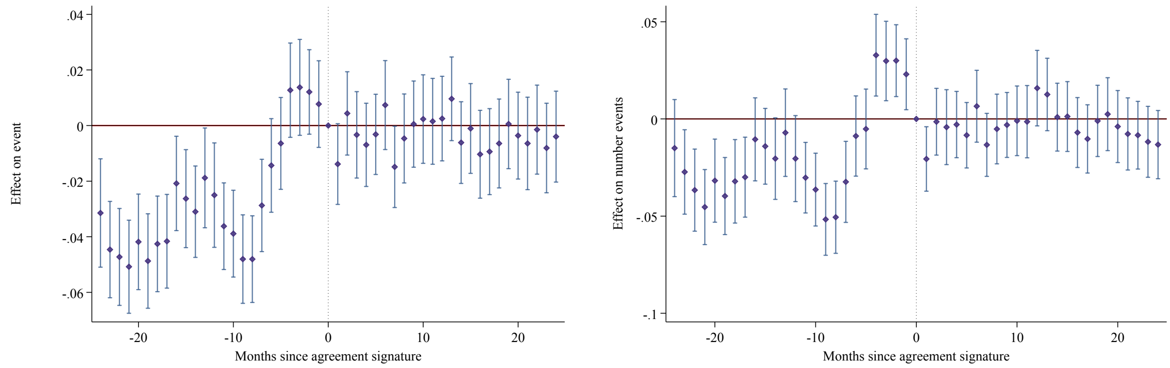


Notes: This figure considers the last agreement signed per actor for a scatterplot of conflict events, prevalence (left panel) and intensity (right panel), by signatory status against the time window of 24 months before and 24 months after the signing.

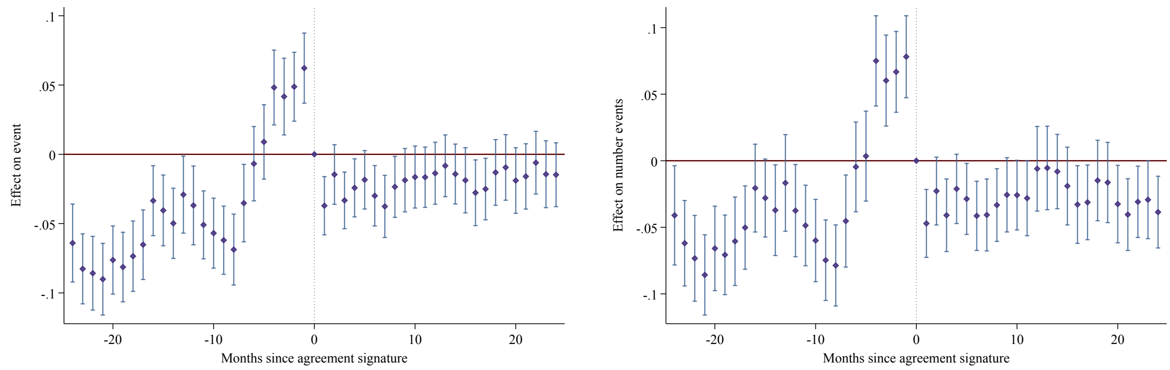
D Robustness checks

Figure D1: Event study of peace agreement on conflict prevalence/intensity (1st agreement, include never treated)

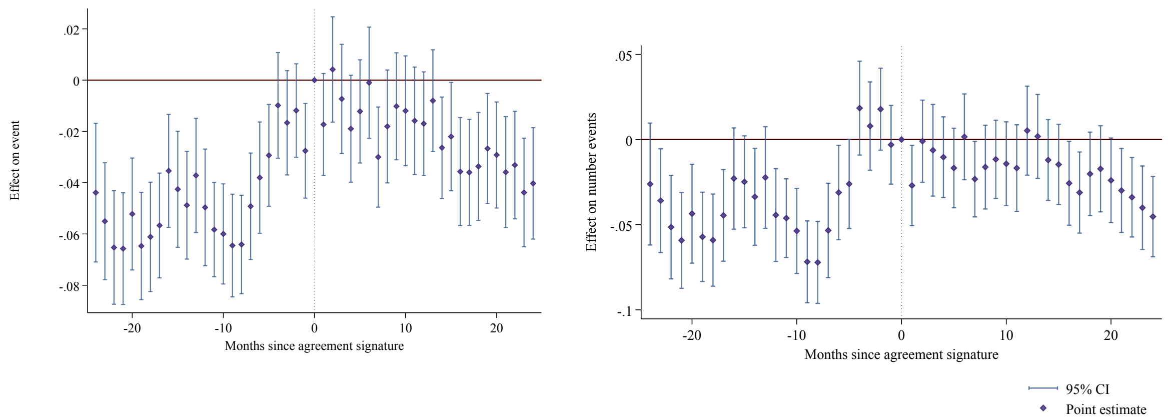
(a) Panel A: full grid-cells



(b) Panel B: ante grid-cells



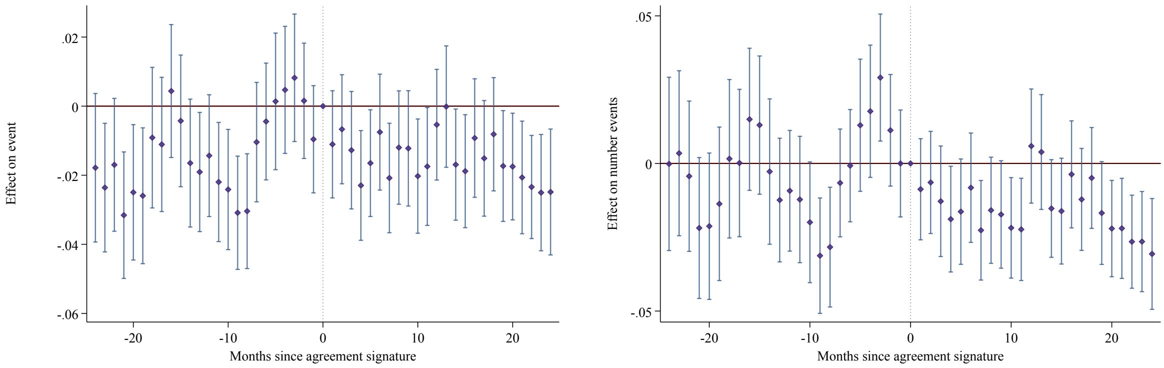
(c) Panel C: post grid-cells



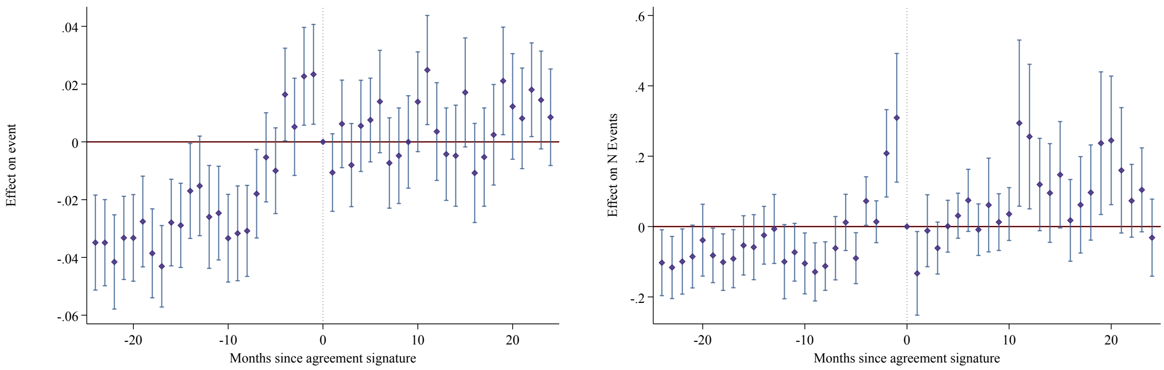
Notes: Event study graphs depicting the dynamics 24 months before and after the peace agreement signature on outcomes of conflict prevalence (left) and conflict intensity measured in number of events (right).

Figure D2: Event study of peace agreement by type (1st agreement, include never treated)

(a) Panel A: Ceasefires



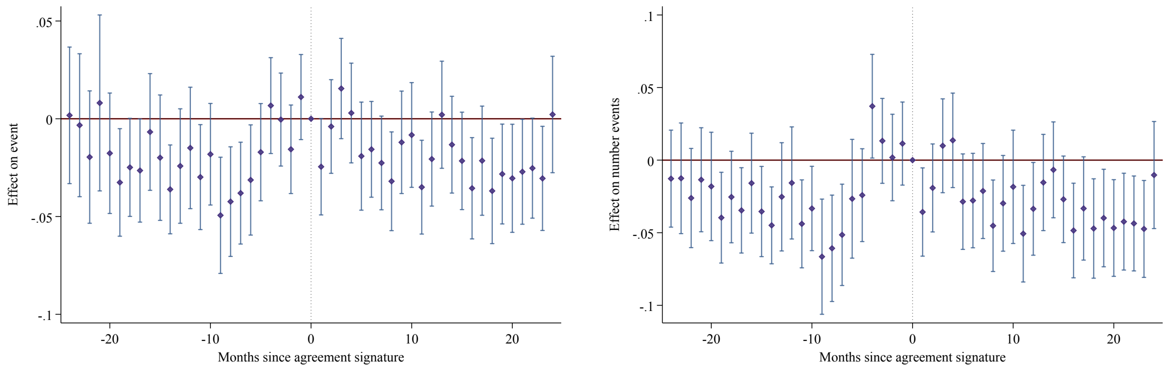
(b) Panel B: Pre-negotiation



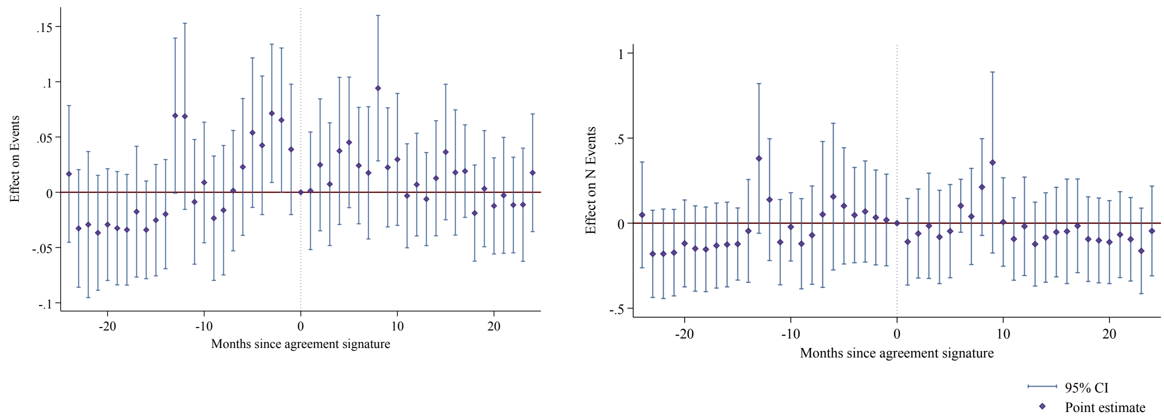
Notes: Event study graphs depicting the dynamics 24 months before and after the peace agreement signature on outcomes of conflict prevalence (left) and conflict intensity measured in number of events (right).

Figure D3: Event study of peace agreement by type (1st agreement, include never treated)

(a) Panel A: Substantive framework, partial



(b) Panel B: Substantive framework, comprehensive



Notes: Event study graphs depicting the dynamics 24 months before and after the peace agreement signature on outcomes of conflict prevalence (left) and conflict intensity measured in number of events (right).

Table D1: Trend breaks estimates of peace agreements' effect on violence (1st agreement, include never treated)

	Event			Number of events			Number of fatalities		
	(i)	(ii)	(iii)	(iv)	(v)	(vi)	(vii)	(viii)	(viii)
π_1	-0.008	-0.059***	0.004	-0.010	-0.061***	0.000	0.001	-0.053***	0.017
	(0.006)	(0.013)	(0.008)	(0.009)	(0.018)	(0.010)	(0.012)	(0.017)	(0.015)
π_2	0.002***	0.005***	0.002***	0.002***	0.005***	0.002***	0.002***	0.005***	0.002**
	(0.000)	(0.001)	(0.000)	(0.000)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
π_3	-0.002***	-0.004***	-0.003***	-0.002***	-0.004***	-0.003***	-0.002**	-0.003***	-0.002**
	(0.000)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
N	47	47	47	47	47	47	47	47	47
Control-mean ante	0.068	0.068	0.073	0.119	0.118	0.127	0.059	0.064	0.069
Grid-cell selection	full	ante	post	full	ante	post	full	ante	post

Robust standard errors are reported in parentheses, *, **, and *** indicate significance at the 10%, 5%, and 1% levels.

Table D2: Trend breaks estimates of ceasefire and substantive framework agreements' effect on violence (1st agreement, include never treated)

	Ceasefire		Pre-neg		SF part		SF comp	
	Event (i)	N Event (ii)	Event (iii)	N Event (iv)	Event (v)	N Event (vi)	Event (vii)	N Event (viii)
π_1	-0.011*	-0.016**	-0.010	-0.010	0.004	-0.003	-0.013	-0.007
	(0.006)	(0.008)	(0.007)	(0.009)	(0.009)	(0.013)	(0.016)	(0.070)
π_2	0.001***	0.001	0.002***	0.002***	0.000	0.001	0.004***	0.008**
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.001)	(0.001)	(0.003)
π_3	-0.001**	-0.001	-0.002***	-0.002**	-0.001	-0.002**	-0.006***	-0.015***
	(0.000)	(0.001)	(0.000)	(0.001)	(0.001)	(0.001)	(0.001)	(0.005)
N	47	47	47	47	47	47	47	47
Control-mean ante	0.069	0.068	0.063	0.059	0.066	0.062	0.064	0.060
Grid-cell selection	full	full	full	full	full	full	full	full

Robust standard errors are reported in parentheses, *, **, and *** indicate significance at the 10%, 5%, and 1% levels.

Chapter 2

Gone with the wind: the welfare effect of desert locust outbreaks

Joint with Stefano Tripodi

2. Gone with the wind: the welfare effect of desert locust outbreaks

*Joint with Stefano Tripodi**

Summary

Desert locust outbreaks and other pests pose a significant threat to food security for millions of people. In this paper we quantify the size of the productivity and welfare loss caused by a desert locust outbreak that hit Ethiopia in 2014. We identify the causal effect of locust swarms on agricultural output and children's nutritional status by modelling swarms' movements based on wind speed and direction to identify areas in which they likely land (*affected areas*). We corroborate our finding by using a "recentered" measure of exposure to swarms that removes the bias due to non random exposure. We find that agricultural output is about 10-11% lower in areas hit by the shock compared to areas that are not affected. On average, children nutritional status is not negatively impacted by the shock, but each additional swarm affecting an enumeration area decreases BMI and weight-for-height z-scores by about 0.03 standard deviations, compared to children living in non affected areas.

2.1 Introduction

Farm households in low income countries are often exposed to large negative productivity shocks. These shocks may severely affect household welfare, especially if households practice subsistence farming and have limited access to insurance mechanisms. Although rainfall variation is usually considered the most important source of negative shocks for farming households, another relatively common type of agricultural risk comes from agricultural, or plant, pests.

Agricultural pests, in particular trans-boundary pests such as locusts, armyworms and fruit flies, have the potential to wipe out farm productions and pastures. Their spread dramatically increased in recent years.[1] Due to their rapid spread, plant pests are difficult to control and can threaten livelihoods and food security of millions at a time. Recently, a massive desert locust upsurge in Eastern Africa, Southwest Asia and around the Red Sea has been declared as one of FAO's highest priorities.

* We would like to thank seminar participants at Copenhagen Business School and at the DGPE workshop for helpful comments and discussion.

[1] https://www.fao.org/emergencies/emergency-types/plant-pests-and-diseases/en.

In this paper, we study how a desert locust outbreak that affected Ethiopia in 2014 impacted farm households. To identify the causal effect of the outbreak on several welfare and economic dimensions, we exploit the fact that desert locusts are passive fliers and fly downwind. Specifically, given the observed position of a desert locust swarm as reported by the FAO Locust Hub, we model the movements of desert locust swarms as if they were particles in the atmosphere using NOAA's HYSPLIT model. We then identify areas in which swarms likely land (*affected* areas) and areas in which we do not predict them to arrive mainly based on wind speed and direction (*non affected* areas). Finally, we overlap the modelled swarm locations with the position of the LSMS enumeration areas and compare communities *affected* by swarms to *non affected* communities. This approach allows us to measure the causal effect of desert locust swarms on farm production, farm assets (e.g. livestocks), household member labour supply (both on- and off-farm), food allocation and children nutritional status. We corroborate our findings by using an alternative measure of exposure, in the spirit of Borusyak and Hull (2021), that removes the bias due to the possibility of non-random exposure to desert locust swarms.

We find that being exposed to desert locust swarms is associated with a decrease of 10-11% in output of total and subsistence crops. This is a considerable effect given the impact is measured two harvesting seasons after the swarms infestation.[2] Households exposed to desert locust swarms have higher off-farm labour supply compared to households that are not exposed. The effect on off-farm labour supply is large in magnitude and corresponds to an increase of 57 to 77%, compared to households that are not exposed. However, on-farm labour supply by household members is not affected by the shock. Similarly, we find no medium run impact on livestocks herd size, and on the number of meals allocated to adults or children. We do not find that desert locusts negatively impact the health of children exposed to the outbreak, measured by body mass index (BMI) z-score and weight-for-height (WFH) z-score, although the point estimates of the effect size are negative. These results are robust to the use of an alternative measure of exposure to the shock. However the intensity of the shock matters. Using the number of swarms an enumeration area is exposed to as proxy for shock severity, we find that being exposed to one additional desert locust swarm is associated with a significant decrease in BMI and WFH z-scores of 0.031 and 0.032 standard deviations, respectively.

We contribute to the following strands of literature. First, the measurement of plants pests' impact on economic and health outcomes, (see e.g. Banerjee et al., 2010; De Vreyer

[2] LSMS waves are conducted in 2012/13 and 2015/16.

et al., 2015; Conte et al., 2021), with the latter two discussing desert locusts in Mali during the plagues of 1987/89 and 2004/05, respectively. De Vreyer et al. (2015) find a negative long-term impact on educational attainment for children born during the plague, with girls being hit harder. In their recent study, Conte et al. (2021) disentangle two channels: a speculative/anticipatory price effect that impacts during the growing season, and a local crop failure effect that affects the households after the harvest. Looking at health outcomes of children exposed in utero, they show differential impacts depending on the channel present and find that market integration plays a critical role in alleviating the consequences of the negative agricultural shock. In contrast to the latter study, we use a different method to identify *affected* communities, which takes into account the determinants of desert locust movements and the probability of communities exposure.

Second, the paper more broadly relates to household and individual level responses to income shocks: considering the impact on child health and gender-biased re-allocation preferences (e.g. Alderman et al., 2006; Jayachandran and Pande, 2017); their persistence (Bekar, 2019) and the limited capacity of household's to insure themselves against it (Porter, 2012; McKenzie, 2003; Dercon and Krishnan, 2000).

The remainder of the paper is organised as follows. Section 2.2 provides a synopsis of the state of the art understanding of desert locust's behaviour, and describes the main characteristics of the agricultural sector in Ethiopia. Section 2.3 presents the different data sources and corresponding sample characteristics of the analysis. Section 2.4 lays out the measurement of the desert locust outbreak by treatment assignment strategy, the identification of the impact in the reduced form, and its translation to the empirical strategy. Section 2.5 reports estimates on the effect, and discusses their heterogeneous nature and, in Section 2.6 we conclude and discuss avenues for future research.

2.2 Background

2.2.1 Desert Locusts

Desert locusts (*Schistocerca gregaris*) are member of the grasshopper family *Acridadae*, but differ from the most common grasshopper because of their ability to change their behaviour and their physiology in response to environmental stimulus. When their density increases, they gregarize and form dense and large swarms. Swarms can cover areas of several hundred km^2, with a density of around 50 million individuals per km^2 (50 individuals per m^2) (Simmons and Cressman, 2001). Desert locust swarms are highly mobile and their movements depend on wind direction and speed. Locust swarms fly downwind and they can fly continuously for 9-10 hours per day in warm temperatures, easily covering distances of about 100 kilometres (although it's not uncommon for swarms to cover larger distances).

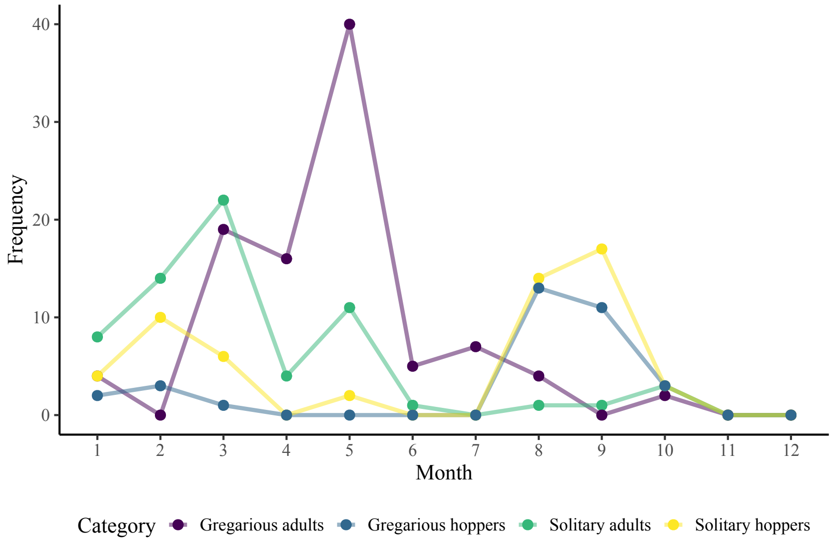
Desert locust swarms represent a significant threat to food production and security in a region. A single desert locust consumes food equal to its own bodyweight in a single day and a swarm of 1 km^2 can consume in a day the same amount of food consumed by 35,000 people (FAO, 2016). Estimates of the impact of the 2003-2005 desert locusts plague in West Africa suggest losses in expected cereal production of about 80 to 100%. Besides the immediate threat to food security, desert locust outbreaks can have persistent effects on socio-economic measures and can exacerbate other shocks, such as drought and conflict (Barret, 2010).

Ethiopia is among 25 countries in Asia and Africa where desert locust infestations are normally present throughout the year (such areas are called *recession areas*). As such, Ethiopia has been constantly exposed to desert locust infestations, although the FAO did not report any major outbreak or upsurge before 2019 and the last outbreak was reported between October 1997 and June 1998. However, the incidence of locusts infestations increased over time, and reports of single events have become more common since 2006-2007 (Figure C1).

In this paper, we focus on a desert locust outbreak that began during the first months of 2014. In January 2014, the Desert Locust Bulletin raised concerns about some groups and small swarms moving towards eastern Ethiopia from Somalia and Djibouti. Despite some efforts to treat and contain swarms coming from adjacent countries and local breeding, in March and April several swarms moved into Ethiopia and began laying eggs, eventually moving inland and reaching Addis Ababa in May. The fact that the first swarms were not the product of local breeding, but rather entered Ethiopia from neighbouring countries implies that farmers could have not foreseen swarms formation.

Figure 2.1 shows the evolution of the 4 types of locust events recorded by FAO (including those in a 80 km buffer in neighbouring countries) in 2014. This Figure also shows the typical progression of a locust outbreak. First, we observe a marked increase in the number of reported solitary adults between January and March. As the gregarization process starts, the number of reported swarms starts to increase and eventually reach its peak in May. Swarms are then dispersed, either naturally or through control operations. However, eggs laid in the previous months hatch. This corresponds to increasing numbers of hoppers, both solitary and gregarious, as observed between July and September. Although this increased number of solitary individuals can be the starting point of a new and larger outbreak, in 2014, this did not happen and the outbreaks was eventually contained, as no new swarms were reported after October.

Figure 2.1: Number of desert locust events in Ethiopia in 2014



Notes: This figure shows the progression of 4 different types of desert locust events (gregarious adults, gregarious hoppers, solitary adults and solitary hoppers) in Ethiopia and neighbouring countries in 2014.

2.2.2 Ethiopia

Agriculture plays a central role in Ethiopian economy, where about 12 million smallholder farming households account for about 95 % of total agricultural output and 85 % of all employment. Agriculture and livestock production account for about 43 and 45 % of GDP, respectively. The agricultural sector is dominated by subsistence farming, which accounts for about 90% of the annual gross agricultural output. Agricultural production in Ethiopia follows two main seasons: Belg season, with planting from February to April and harvesting from March to August, and Meher season, with planting from April to October and harvesting from September to May the next year.

Providing a general characterization of the Ethiopian agricultural system is difficult, as its climate varies significantly across regions, especially in terms of precipitation. In general, the highlands of Ethiopia show more predictable rainfall, while Ethiopian lowlands present a more erratic rainfall pattern. This climatic diversity creates distinct agroclimatic regions that favour different crop and livestock. In the dry eastern part of the country, crop production is limited and the main agricultural activity is livestock rearing. The highlands, on the other hand, provide ideal conditions for cereal growing (Wolfrey et al., 2021).

Rural land is government owned and it is controlled by the Peasant Association. Peasant Associations represent the lower level of government in Ethiopia and periodically redistribute land to households, primarily according to family size. As such, agricultural land can not be legally sold by individual farmers. In order to be eligible for land allocation, a farmer has to register to the local Peasant Association when he turns 18 or before marriage (Gavian and Ehui, 1999).

Thanks to some improvements in agricultural productivity, food security in Ethiopia has improved in the last two decades. Nonetheless, food insecurity remains a severe problem: about 20% of the population is undernourished, 37% of the children suffer from stunting and 10% suffer from wasting (low weight-for-height). Food insecurity is also widespread among adolescents, with about one out of five adolescents in Southwestern Ethiopia being categorized as food insecure (Belachew et al., 2011).

Significant gender inequalities persist in Ethiopia. Women in Ethiopia have on average lower levels of education than men and are significantly less likely to participate to financial markets or to income generating activities (Wolfrey et al., 2021). Anthropological evidence suggests that as one moves from the north to the south of the country, women's status declines. Again, this generalisation masks important heterogeneity because of the large cultural and ethnic variation in the country (Fafchamps and Quisumbing, 2002). Rules regarding divorce and inheritance for example are more patriarchal in the Muslim and Protestant areas (East, West and South) and more egalitarian in the orthodox areas (North).

Arranged marriages are the norm and patrilocality, which means that the bride moves into the groom's place of residence, is widespread. One implication of this practice is that grooms bring the largest part of start-up capital to the marriage (about 10 times more than what the bride brings). However, control over household resources is primarily in the hands of the household head, irrespective of its sex. Decision on what to grow and financial management are centralised. Most of the livestock owned by the household is held jointly by the husband and the wife.

2.3 Data

This section provides information about the main data sources and the variables used in the paper. More details appear in the Appendix Section A.1.

The baseline structure of the dataset consists of a panel with two waves of household- and individual-level data that span over the period from 2013 to 2016 and include households in rural areas and small towns in Ethiopia.

2.3.1 Locust data

The data about locust events, i.e. the report of location, date and characteristics of observed isolated adults, isolated hoppers, hopper bands or swarms, is publicly available through the FAO Locust Hub.[3] As swarms are highly mobile, the coordinates reported in the data represent the location where they are observed on, or in close proximity to, the ground. We include in our study swarms reported in the lands of Ethiopia and neighbouring countries within a buffer of 80km from the national Ethiopian border, accounting for the high mobility of the swarms. For 2014, we identify 97 different swarms, most of them observed in May and August/September.[4]

2.3.2 Household- and individual-level data

We take household- and individual-level data from two Ethiopia Socioeconomic Survey (ESS) waves. The waves currently available cover the periods 2011-2012 (wave one), 2013-2014 (wave two) and 2015-2016 (wave three). In this paper, we only focus on the second and the third wave, that is the wave immediately before the onset of the desert locust outbreak and the wave after.[5] The surveys have been implemented by the Central Statistics Agency of Ethiopia and the World Bank Living Standards Measurement Study (LSMS).

Each survey is organised in three questionnaires, community, household and agriculture, where the latter is divided into three modules of post-planting, livestock and post-harvest. These modules are implemented in three different visits to the household accounting for the agricultural seasons in Ethiopia. A household is understood in its standard definition as an economic unit, where a group of people live together, pool their money and eat at least one meal together each day. The head of the household is determined by household members and is usually the main income earner and decision-maker for the household.

12 households are interviewed in each rural and small town enumeration area. The coordinates of the household are provided at the enumeration area and not at the individual level. To further preserve anonymity of the respondents, ESS data offsets the coordinates of the enumeration areas in a random direction by 10km. In our analysis, we therefore exclude enumeration areas that are of different treatment status and

[3] https://locust-hub-hqfao.hub.arcgis.com

[4] For all 97 identified swarms the date precision is qualified as "imprecise" by FAO. We account for this imprecision by including a bandwidth of plus/minus 5 days around the reported date in our calculations using meteorological data in Section 2.4.1.

[5] We disregard wave 1 due to changes in the sampling procedure and the inclusion of different enumeration areas from wave 1 to wave 2.

less than 10km away from each other, as we believe this is the most conservative approach.[6] From the original 434 unique enumeration area IDs reported in the data we exclude five due to data entry error and 235 due to either lying in large towns and/or due to their position outside of the potential grounds of locust swarms' activity in Ethiopia.[7] The balanced household-level sample consists of 194 enumeration areas including 2138 households. For child-level analysis, our dataset is based on 192 enumeration areas with 940 households.

In the first ESS wave, anthropometric measures (weight and height/length) were taken for children from 6 to 59 months.[8] This is because after 5 years of age weight and height can reflect not only the nutritional status of a child, but also its genetic characteristics. In subsequent waves, measures were taken for children from 6 to 83 (wave two) and from 6 to 107 months old (wave three). With the threshold for measurement increasing in each wave, children who were measured in wave one can be re-measured in wave two and three.

In order to compare the nutritional values of these children across time or socioeconomic grouping, we transform the measures of children's weight-for-height and body mass index (weight/height^2) to standard deviation z-scores. The z-scores are standardised to the WHO reference population for the child's age and gender, removing skewness and adjusting for physiological changes in anthropometric measures that occur with age using the LMS method (Cole, 1990; Vidmar et al., 2004).[9] A z-score with absolute values of one reads as one standard deviation away from the mean. We chose to study BMI z-score and weight-for-height z-score, as they provide a measure of child wasting and respond to short-term fluctuations in nutritional intake. We disregard z-scores with absolute values greater than or equal to five in an attempt to capture extreme data entry errors, as well as measurement entries below or equal to zero

[6] The geolocations of enumeration across wave two and three are not unique in 5.3% of the cases. The imprecision between registered locations for the same enumeration area measures a distance of min 2 km and max 11 km. To account for this imprecision in registered coordinates, we average the longitude and latitude degrees across waves to create a unique middle location. This also accounts for the fact that the GPS technology used may have improved over time.

[7] The five excluded IDs in wave two and three concern the following: one is a duplicate in terms of location and household characteristics; two are positioned outside of Ethiopia in the same location, suggesting that they might be the same enumeration area in actual fact; two enumeration areas that are differently affected by locust swarms in 2014 and are closer than 10km to each other.

[8] Children between 6 and 24 months old are measured lying down (length), and children aged between 24 and 59 months are measured standing up (height).

[9] The LMS method provides a way of obtaining normalized growth centile standards, based on three curves: smooth (L) curve summarises the trend of the obtained optimal power for normality calculated for each of a series of age groups; trends in the mean (M) and coefficient of variation (S) are similarly smoothed curves. The WHO standards were developed using the WHO Child Growth Standards (0-5 years) and WHO Reference 2007 (5-19 years) composite data files that are based on data collected in the WHO Multicentre Growth Reference Study.

of height and weight. We impute missing values for z-score by predicting them using a random forest algorithm, as described in Appendix Section A.3. We furthermore categorise children aged 24 to 107 months according to their body mass index into thinness grades, normal weight, overweight and obese, using WHO cut-off points.[10]

The sample for the individual regressions of children is restricted to the presence of each child in both waves and being within the age range for anthropometric measurement, resulting in 1459 children.[11]

The post-planting module of the ESS survey includes questions about harvest in the previous agricultural season, as well as labour and capital inputs applied to each plot. The variables relevant for this paper are those related to household agricultural production from own fields. We calculate total output as the sum of (self-reported) agricultural output produced across each field the household cultivates. Moreover, we also calculate total subsistence output as the sum of (self-reported) output from subsistence crops in the same way. We define subsistence crops as those who are commonly consumed (and less likely to be sold) by Ethiopian rural households.[12] We also compute total cultivated area and area cultivated with subsistence crops, as well as a measure of total working days applied on household plots.

The livestock module collects information about livestocks owned by households, as well as information on livestock products produced and sold. We calculate total household livestock holding by converting each animal into TLUs (Tropical Livestock Units).[13] This makes it possible to describe livestock numbers across species and to calculate the "total amount" of livestock owned.

The household module includes socioeconomic information about each member of the surveyed household. We use household member's information to obtain measures about the member's sex, religion, education, labour market participation and income earned in the last 12 months.

In our analysis, we restrict the sample to households living in administrative zones where at least one swarm was observed between 1985 and December 2013, that is

[10] Where a body mass index (kg/m^2), < 16 is categorised as Grade 3 thinness; 16 to < 17 as Grade 2 thinness; 17 to < 18.5 as Grade 1 thinness; 18.5 to < 25 as Normal weight; 25 to < 30 as Overweight; and > 30 as Obese.

[11] We check for attrition bias comparing the balanced sample of children across the two waves to the children that were in wave two but not in wave three, for reasons other than anthropometric measurement restrictions, see Appendix Section A.2.

[12] Subsistence crops include barley, chick peas, field peas, haricot beans, horse beans, lentils, maize, millet, sorghum, teff and wheat.

[13] We consider a mature cow (250kg) as the reference livestock category and apply different weights to other animals to obtain their TLU value (Njuki et al., 2011), e.g. one cow is 1 TLU, one sheep is 0.1 TLU, one camel is 1.25 TLU. We then sum all TLUs to obtain total household livestock holding.

during the period prior to the outbreak of 2014.[14] The zones affected are a result of general wind directions in Ethiopia and likely distances travelled by swarms based on their reported location in the FAO Locust Hub dataset.

2.3.3 Weather data

To account for local differences in the probability to be affected by locust swarms and generally for local income differences among the households, we use climatic and vegetation information at the enumeration-area level. In particular, we use precipitation, temperature, humidity and two vegetation indices (low, high) from the ERA5-Land monthly reanalysis dataset of 0.1×0.1 degrees latitude-longitude resolution, from the Copernicus Climate Change Service (Sabater, 2019).[15] We overlap the enumeration areas' location with the gridded ERA5-Land dataset, and calculate deviations from the historical mean (past 30 years) of the annual averages in the years of our survey waves. Deviations from the long term mean account for climatic frictions where negative or positive deviations create conditions that foster locusts to spread, and impact agricultural production directly. For wave two and three we use the historical average at the grid-cell level across the years 1982 until 2012, and 1984 until 2014.

2.3.4 Ethnicity data

Ethiopia is characterized by substantial ethnic diversity. Since characteristics of ethnic groups are persistently and strongly associated with modern day cultural, geographical, and environmental factors (e.g. Michalopoulos and Papaioannou, 2013; Anderson, 2018), we include in all our specifications ethnicity fixed effect. To identify the dominant ethnicity in an Enumeration Area, we overlay their location coordinates with the George P. Murdock Ethnolinguistic Map for the African continent Murdock (1959), which maps the spatial distribution of ethnicities during pre-industrial times. Fifty different groups are identified in Ethiopia alone. We assume that individuals who reside in the same ethnic homeland will share the same cultural norms and traits and, that the spatial distribution of ethnicities in Ethiopia did not change substantially since the map has been created.[16] Our household-level sample extends over the territories

[14] A zone is the second level of administrative subdivision of Ethiopia after regions and before districts, *woreda*. There are 79 different zones with an average size of 14298 km^2 where the smallest covers 8.66 km^2 and the largest 62048 km^2.

[15] Reanalysis data combines model data with observational ones using laws of physics to create a consistent and accurate view of the evolution of the climate going back several decades in time. The spatial extent rests on a native spatial resolution of 9km on a reduced Gaussian grid (TCo1279).

[16] The logic that ethnic traits are spatially attributable to the people living in areas dominated by an ethnic group, or vice versa, is similarly employed in the existing literature, e.g. Michalopoulos and Papaioannou (2013) use it to measure the average income of ethnic groups. We verify the accuracy of the ethnic boundaries based on the Murdock Ethnolinguistic Map using the two rounds of the

of 23 different dominant ethnic groups of Ethiopia.

2.3.5 Sample characteristics

Table 2.1 describes the characteristics of households in the sample and, for a subsample the respective characteristics of children and their mothers at baseline (wave 2). A large majority of our households are in rural areas, 88%, compared to 12% in small towns.

As reported in Panel A in Table 2.1, a household consists on average of 5.5 members. The head of the household is predominantly male (74%) and on average 46 years old. A large majority of the households cultivates crops (80%) and holds livestock (77%), suggesting that crop cultivation and livestock rearing are complementary activities. The average production output is 0.09kg/m^2 and households own on average g 5.3 livestock TLU. Farm labour is predominately supplied by household members, which work on average 365 days annually. Hired labour on own plots is about 3% of household labour. Household members work mainly on the household farms, as suggested by the small amount of off-farm labour working days. To proxy household income, we consider annual household consumption expenditures (which includes food, non food and schooling expenditures) that on average measures at 9.7 log units.

Considering the child-level sample, reported in Panel B and C in Table 2.1, we match a mother present in 96% of the cases. The level of education of the mothers is low: 21% report to have attended school with a comparably low level of reading and writing skills attainment. The self-reported income of the mothers is reported at a fraction of the average household consumption expenditures, at 1.2 log units. The children are balanced with respect to gender, on average 45 moths old and have 1.5 other sibling under the age of 83 months at baseline. The children in the sample are on average stunted in terms of both body mass index z-score and weight-for-age z-score, with 0.23 and 0.53 standard deviations below the mean. The anthropometric measures used are by design similar across gender.

Finally, Panel C in Table 2.1 reports the average levels in terms of deviations from the 30 years historical means. On average, for all variables considered, the enumeration areas included in this study present positive deviations from the 30 years historical means in wave 2.

Afrobarometer surveys on Ethiopia (2013, 2020), which code self-reported ethnicity of respondents and the exact location (longitude, latitude).

2.4 Measuring the impact of desert locusts

This section describes the identification of households that are *affected* by locust swarms observed in Ethiopia and close border areas in 2014. Next, we discuss the empirical strategy we use to estimate the effect of the agricultural shock.

2.4.1 Treatment assignment

In order to determine the areas likely *affected* by the locust swarm invasions, the assignment relies on the animals' behaviour to be heavily influenced by climate and weather conditions. In particular, we exploit the fact that desert locusts are passive fliers and drift downwind most of the time.[17] Hence their flight trajectories are impacted by varying meteorological conditions in the atmosphere. The likely infested area is predicted on a series of trajectories that use the desert locust swarms' observed location and time, combined with prevailing air mass movements to calculate where the swarms came from and where they are going to.

To calculate the air mass trajectories the locust swarms are likely transported by, we use NOAA's HYSPLIT model (Stein et al., 2015).[18] The model runs on input data of the observed location and timing of the swarm close to the ground and meteorological data that consists of previously computed, gridded reanalysis data, e.g. wind speed and direction, temperature, humidity, pressure and precipitation.[19]

In the following, we outline the model parameters used to describe the likely flight trajectories of desert locust swarms: (i) the flight time, (ii) the flight height and (iii) the date of the flights. First, swarms are reported to primarily fly during the day (after sunrise and before sunset), hence, we limit the possible flight time by specifying start

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[17] In other words, swarms as passive fliers balance dispersion dynamics in order to move as unified air parcels. Such air trajectory calculations are common in atmospheric analyses, mainly focusing on the transport of pollutants via such trajectory routes to examine their origin as well as their destination given atmospheric conditions.

[18] The National Oceanic and Atmospheric Administration (NOAA)'s Hybrid Single-Particle Lagrangian Integrated Trajectory model (HYSPLIT), is widely used in atmospheric studies to simulate backward and forward trajectories of air masses at any grid point on Earth. Furthermore, these models are used to track air quality by estimating the downwind ambient concentration of air pollutants or hazardous material as they are atmospherically transported, dispersed, and deposited. See Stein et al. (2015) for an overview of the historical evolution of the model over the past 30 years. In light of the severe outbreak in early 2020, NOAA's HYSPLIT model was adapted to the needs of FAO to issue forecasts and warnings about potentially devastating second wave swarms to affected countries. The collaboration also includes a web application https://locusts.arl.noaa.gov:8443; NOAA news release note see https://research.noaa.gov/article/ArtMID/587/ArticleID/2620/NOAA-teams-with-the-United-Nations-to-create-locust-tracking-application.

[19] The data was downloaded from the NOAA FTP server prior to running the model. The paper uses the SplitR package that creates a R interface to NOAA's HYSPLIT model, see https://github.com/rich-iannone/splitr.

and end time to be on the same date during day light.[20] Second, to allow for a minimum distance before the trajectories necessarily are drawn to the ground, an initial height of 50 meters above ground is assumed. While this is a stark approximation as swarms take-off from the ground or trees, the resulting average height along all the trajectories is reported at 210 meters above ground, and representative of observed behaviour. Third, we account for the imprecise date of locust swarm observation by using a bandwidth of five days plus and minus from the reported date, hence per observed locust swarm we register ten possible dates to calculate likely forward trajectories, where the swarm is going to, and likely backward trajectories, where the swarm is coming from. The final measure will be a mean trajectory across these multiple dates of potential flight, accounting for various uncertainties of measurement and varying meteorological conditions.

The key assumption to use the HYSPLIT model to calculate average flight trajectories of locust swarms is their approximation as unified air parcels where dispersion dynamics due to atmospheric instability are counterbalanced by active, collective swarm behaviour. Swarm intelligence prevents the swarm to be broken up in the air, but rather keeps them all together until the destination. Furthermore, we assume that they are in the air until the end of the flight that day. This treatment assignment is not accounting for conditions of vegetation or temperature at which locusts are more likely to take off or land.

Figure 2.2 illustrates the calculations across time per single swarm (red dot) observed at date t. In the baseline specification, we predict locations of infestation using average trajectories across three days d_{-1}, d_0, d_{+1}: one backward trajectory (blue) and two forward trajectories (dark red and green). The backward trajectory for day d_{-1} takes the location of day d_0, i.e. the observed swarm location at date t, as destination location of day d_{-1} and calculates the origin of this trajectory backwards based on meteorological conditions at $t-1$. The first forward trajectory uses the original location and conditions at t to calculate end of day d_0 flight destinations. The second forward trajectory uses the destinations of day d_0 as starting positions and finds the respective end positions for day d_{+1} using conditions of $t+1$. The trajectories are measured for a bandwidth of $t \in (t-5, t+5)$, with 50 randomly selected landing/starting times for the backward trajectories on day d_{-1}, the forward trajectories on day d_0, whereas for the forward trajectories on day d_{+1} it is limited to five different starting times given

[20] While the start time is taken at face value, the landing time depends on the meteorological conditions that day, where the indicated landing time defines the maximum, yet shorter flights can occur if pressure or wind dynamics pressure the trajectories close to the ground early on. The start and landing times are normally distributed, local time around 8 in the morning, 17 in the evening (ranging between 7 to 10 until 4 to 19 o'clock).

the many starting positions, i.e. the end positions of day d_0.

To calculate a measure of locust propensity for each enumeration area, we simulate swarm trajectories each year for 15 years prior to the observed swarm. We do so by repeating the algorithm described above for each swarm keeping everything fixed but the year. For each year and each swarm, we obtain the area in which the swarm can be located, given a year's wind speed and direction. We then calculate the propensity of an enumeration area to be hit by desert locust swarms as the average number of swarm concave polygons that intersect that enumeration area.

In Figure 2.2 the three day trajectories across the bandwidth of dates considered for a single swarm are represented with dots for the hourly positions along each trajectory. Similar starting times with corresponding meteorological conditions may lead to convergence in trajectories. We calculate the hourly average position per same date t per locust swarm, illustrated by the darker dots.

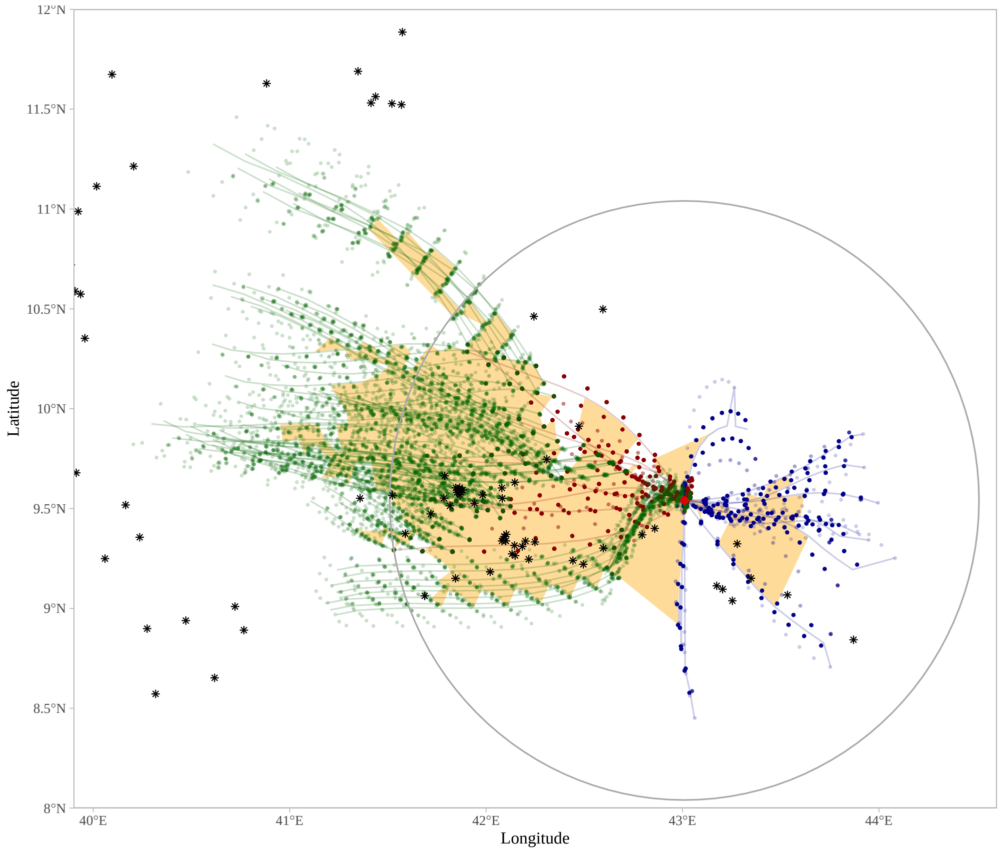
A swarm may fly up to nine or ten hours a day (FAO, 2016), for the baseline specification we assume a maximum flight time of seven hours per day. The likely infested area by an observed swarm is calculated as the area within the concave polygon containing all hourly positions along the average trajectories of up to seven hours of flight time per day.[21] An enumeration area is considered *affected* when its longitude and latitude coordinates intersect with the area predicted to be likely infested by any locust swarm, and *non affected* in the opposite case. Figure C3 shows the modelled, three days trajectories of the 97 identified swarms in 2014, with the *affected* and *non affected* enumeration areas consequently (blue and red crosses). We validate our approach by intersecting the position of all the desert locust swarms observed in Ethiopia since 1985 with the concave polygons we obtained using the HYSPLIT model, excluding the swarms observed in 2014.[22] 87% of the concave polygons contains at least one swarm observed, which suggests that our approach identifies areas that are likely to be infested by desert locust swarms.

In contrast to our approach, the buffer (circle line) around the observed location of the swarm in Figure 2.2 illustrates an alternative assignment approach, see Conte et al. (2021); De Vreyer et al. (2015) for applications. Based on the swarms behaviour, this method could be imprecise the further away from the buffer centre one assigns treatment, as the locust swarms have little chance to reach locations that face opposing

[21] The concave polygon is calculated using the algorithm from the R package `concaveman`, which can be accessed at https://CRAN.R-project.org/package=concaveman. The use of a concave compared to a convex polygon for example is a more conservative measure.

[22] We exclude swarms observed in 2014 since concave polygons are calculated using these swarms, which would then be mechanically included and would give an accuracy of 100%.

Figure 2.2: Three days trajectories of a single desert locust swarm in 2014



Notes: This figure shows the forecasted and backcasted trajectories for one swarm, based on the model described in Section 2.4.1. Red dots and trajectories correspond to the one-day-ahead forecast from the observed swarm position; green dots and trajectories correspond to the two-day-ahead forecast, and blue dots and trajectories correspond to one-day-behind backcast. The yellow area corresponds to the *affected* area. Black dots represent enumeration areas. The circle is a 80km buffer around the observed swarm position.

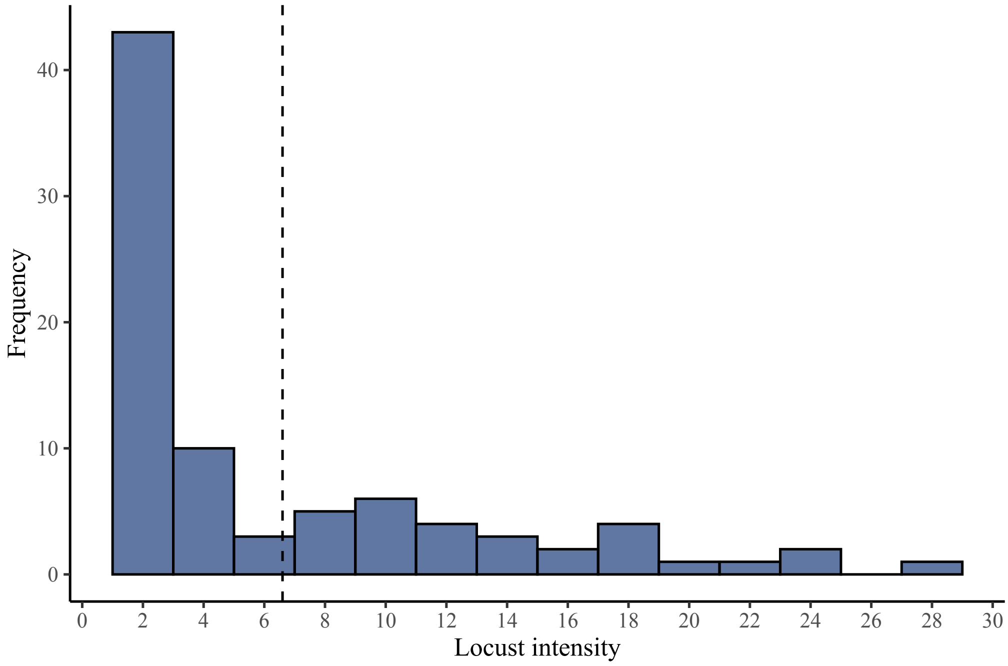
wind dynamics.

Of the 194 enumeration areas left after removing the relevant enumeration areas (as described in Section 2.3.2), 85 are assigned to the *affected* status and the remaining 109 are assigned to the *non affected* status. On average, an *affected* area was hit by 6.6 desert locust swarms. 50% of the *affected* enumeration areas experienced 3 desert locust swarms. The distribution of the number of swarms that hit *affected* areas is shown in Figure 2.3. In total, 935 households and 579 children aged 6 to 107 months live in *affected* areas, while 1203 households and 880 children live in *non affected* areas.

2.4.2 Identification

We identify the causal effect of desert locust swarms by comparing outcomes in *affected* enumeration areas to outcomes in *non affected* enumeration areas, as defined in the Sec-

Figure 2.3: Intensity of the shock



Notes: This figure shows the distribution of the number of desert locust swarms that hit *affected* enumeration areas. The dashed vertical line shows the mean frequency.

tion above. Our approach, based on the observed position of desert locust swarms as reported by the FAO Locust Hub database and on the passive-fliers nature of desert locusts, addresses the problem that observed swarm positions can be endogenous. Specifically, endogeneity in the observed position reported by the FAO can arise because of (i) unobservables that are correlated with local agricultural production and observed desert locust position, and (ii) measurement error.

By using the fact that wind speed and direction determine movements of desert locust swarms, whether an enumeration area is *affected* or not is a function of the exogenous wind characteristics and simulation parameters, which do not depend on farm household preferences. By including uncertainty around the observed position characteristics (e.g. date of observation) in our simulations, we account for possible measurement errors. Specifically, for each observed position date, we calculate trajectories for 5 days before and after the reported date and then average across them to obtain the main trajectory. This is important, as wind patterns can vary across days.

However, swarm movements, in particular start flying time and landing spots, are also conditional on climatic and local vegetation conditions. Therefore, the probability that an enumeration area is *affected* is not independent of these variables. If they are correlated with the outcomes of interest, we will obtain biased results without controlling for them. Therefore, in all our specifications we control for several time varying meteorological and vegetation characteristics measured at the enumeration area level, calculated as described in Section 2.3.3. This implies that, within the concave polygon containing predicted swarm positions, each point is equally likely to be a landing spot for swarms, conditional on climatic and local vegetation conditions.

Affected enumeration areas, i.e. those who serve as "treatment" group, tend to be clustered in certain zones of Ethiopia. Although some determinants of exposure to desert locust swarms are exogenous, as mentioned above, others are not, such as the decision to settle in a given area. To take this possibility into account, we estimate our specifications by using a "recentered" instrument (Borusyak and Hull, 2021). We build this instrument by subtracting from the actual exposure variable the locust propensity measure we computed by simulating flight trajectories over the 15 years before the actual shock. This approach removes the bias from the non-random exposure to the shock (Borusyak and Hull, 2021).

Finally, we claim that farm households can not predict whether they will be hit by desert locust swarms. In fact, in order to predict the movements of a desert locust swarm, a farmer would need information about wind speed and direction, air temperature and vegetation not just in his position, but also in the current position of the swarm. This is difficult, if not impossible, in the context of rural Ethiopia. Therefore, we view the shock as unexpected. This implies we rule out the possibility of anticipation effect, that is the possibility that farmers change their production and consumption choices early enough to insure against the shock.

In the third column of Table 2.1 we check that, conditional on meteorological conditions, households living in *affected* and *non affected* areas are similar. We regress different baseline (wave 2) covariates on an indicator equal to 1 for *affected* areas, controlling for meteorological variables and ethnicity fixed effect. We don't find significant differences in household-level characteristics (Panel A), and child-level characteristics (Panel B). Normalized differences are almost always lower than 0.2. When looking at baseline meteorological conditions we find that *affected* areas have a lower low-vegetation index in wave 2.

2.4.3 Empirical strategy

We estimate the effect of the shock on household agricultural output, total household livestock holdings, off-farm household labour supply at the intensive margin and children nutritional status. We do so by estimating an ANCOVA reduced-form model by OLS. For household-level outcomes, we run

Table 2.1: Balance statistics by affected status

	Sample mean	Std. dev.	AF. vs. Not AF.	Std. err.	Norm. diff.	N
Panel A: Household-level characteristics						
Household members	5.544	2.581	-0.277	0.182	-0.148	2138
Household head's age (y)	46.311	15.616	-0.673	1.249	0.044	2138
Household head is muslim, 0/1	0.408	0.492	-0.035	0.054	0.789	2138
Household head is female, 0/1	0.257	0.437	0.01	0.033	0.05	2138
Crop production, 0/1	0.801	0.4	0.04	0.038	-0.174	2138
Livestock rearing, 0/1	0.772	0.419	0.059	0.034	0.068	2138
Farm area (sqm)	7.939	2.646	-0.003	0.261	-0.102	2138
Agricultural output (kg/sqm)	0.095	0.18	0.015	0.011	-0.169	2138
Livestock, (TLU)	5.284	7.952	0.373	0.789	-0.045	2138
Household non-farm labour (d)	42.115	96.637	-6.687	8.047	0.072	2131
Household farm labour (d)	365.155	509.441	-26.236	77.144	0.005	2138
Hired farm labour (d)	10.785	62.343	-0.064	4.179	-0.086	2138
Consumption (log)	9.69	0.745	0.01	0.084	0.354	2062
Household meal count, aged 5y older	2.76	0.669	-0.097	0.093	-0.092	2126
Household meal count, less than 5y	3.293	1.597	-0.316	0.258	-0.284	1349
Household food shortage past 12m, 0/1	1.663	0.473	-0.04	0.056	0.189	2123
Panel B: Child-level characteristics						
Mother present, 0/1	0.956	0.205	0.001	0.024	0.048	1459
Mother age (y)	30.746	7.087	1.169	0.828	0.072	1395
Mother attended school, 0/1	0.206	0.405	-0.039	0.056	0	1395
Mother can read and write, 0/1	0.186	0.39	-0.074	0.056	-0.068	1395
Mother is working (formal), 0/1	0.186	0.389	0.076	0.07	0.073	1395
Mother income (log)	1.168	2.782	0.037	0.381	0.033	1395
Child is female, 0/1	0.496	0.5	0.042	0.049	-0.017	1459
Age (m)	44.785	21.648	2.174	1.655	-0.018	1459
Birth order	1.505	0.675	-0.084	0.052	-0.101	1459
BMI (z-score)	-0.232	1.442	0.116	0.177	-0.095	1459
Weight for height (z-score)	-0.528	1.253	-0.005	0.148	-0.145	1459
Panel C: Enumeration area characteristics						
Precipitation (mm)	0.088	0.674	0.167	0.118	0.11	2138
Temperature (C)	0.536	0.33	-0.014	0.075	0.432	2138
Leafindex low	0.008	0.009	-0.005***	0.001	-0.262	2138
Leafindex high	0.003	0.01	0	0.001	0.166	2138
Humidity	0.049	0.408	0.107	0.089	-0.033	2138

Notes: Differences across groups are calculated by regressing each variable on an indicator equal to 1 if the household is situated in an affected area, controlling for whether the household is rural and meteorological characteristics of the enumeration area (except for the variables in Panel C). Ethnicity fixed effect, and standard errors clustered at the enumeration area level are included. *, **, and *** indicate significance at the 10%, 5%, and 1% levels.

$$y_{hem,t} = \beta S_{em} + \gamma y_{hem,t-1} + \lambda X_{hem} + \delta E_{em} + \xi_m + \varepsilon_{hem,t} \quad (2.1)$$

where $y_{hem,t}$ is the household-level outcome of interest for household h living in enumeration area e and of ethnicity m in wave t, S_{em} is an indicator variable equal to 1 if the household is in a swarm *affected* enumeration area, $y_{hem,t-1}$ is the outcome in wave $t-1$[23], X_{hem} and E_{em} are wave 2 household and enumeration area controls, and ξ_m are ethnicity fixed effects.

For children-level outcomes, we run

[23] In this study, we only use wave 2 and 3 of the three available LSMS rounds for Ethiopia.

$$y_{ihem,t} = \beta S_{em} + \gamma y_{ihem,t-1} + \pi C_{ihem} + \theta M_{ihem} + \lambda X_{hem} + \delta E_{em} + \xi_m + \varepsilon_{hem,t} \quad (2.2)$$

where $y_{ihem,t}$ is either BMI or weight-for-height z-scores. In addition to the variables described in Equation 2.1, we augment the specification in Equation 2.1 by adding wave 2 children covariates, C_{ihem} and wave 2 mother covariates, M_{ihem}. Our parameter of interest is β, which measures the Intention to Treat (ITT) Effect.

We also estimate Equation 2.1 and 2.2 using a measure of shock intensity, instead of S_{em}. Specifically, we calculate the number of swarm concave polygons that overlap with an enumeration area in 2014 to proxy for the intensity of the shock. Finally, we estimate our models using the "recentered" instrument to corroborate our findings. Formally, given our explanatory variable S_{em}, which measures the actual exposure to the desert locust swarms, we estimate 2.1 and 2.2 using $\tilde{S}_{em} = S_{em} - \bar{S}_{em}$, where $\bar{S}_{em}$ is the average number of time a given enumeration area was exposed to the simulated shock exposure over 15 years before the actual shock. We interpret the estimates obtained with this "recentered" measure as the reduced form estimation from the regression of the outcome on an instrument for *affected* status.

In all specifications, we cluster standard errors at the enumeration area level to account for the fact that *affected* status is assigned at the enumeration area-level. Household-level covariates include cultivated farm area in squared meters, household and non-household farm labour supply, indicator variables for crop or livestock farms, household head age, household head gender, household head religion and the logarithm of annual consumption expenditures, which we use as a proxy for household income. Enumeration area-level covariates include meteorological variables and an indicator for whether the enumeration area is situated in a small town. Child-level variables are age (in months) and age squared, child gender and an indicator for missing value imputation in the outcome variable. Mother-level covariates include mother age (in years), age squared, education and an indicator for labour market participation.

2.5 Results

We now turn to the discussion of the results. First, we discuss the effect of the desert locust outbreak on agricultural yields, livestock, non-farm labour and children nutritional status. We view these results as an indication of the size of the economic shock farmers experienced between 2014 and 2016 due to the desert locust outbreak.

2.5.1 Desert locusts and the size of the agricultural shock

We estimate the reduced form Equation 2.1 for agricultural production of all crops and subsistence crops only, as reported in Table 2.2. For each outcome, we estimate Equation 2.1 using the indicator for actual shock exposure ("Unadjusted"-headed columns), as well as using the "recentered" instrument ("Recentered"-headed columns). We also include different sets of control variables, as described in Table 2.2. We find that across specifications the estimates of the impact of the desert locust shock are negative, statistically significant, and of similar size. This suggests that *affected* households experienced an important negative productivity shock during the relevant period. The magnitude of the shock is similar, although slightly larger when controlling for household characteristics.

Based on the estimates, locust swarms are associated with a decrease in total agricultural production of 11%, or 0.505 log units (column 2), compared to *non affected* households. The effect on subsistence crops is larger in size and implies that *affected* households' subsistence crops' production is around 15.5% lower than that of *non affected* households (column 6). The baseline outcomes high significance implies high correlation over time. These effects are considerable given they are measured two harvest seasons after the desert locust shock. The size of the effect slightly increases when we use the "recentered" instrument, but it is consistent to the estimates of the "unadjusted" models. To address a potential concern about the skewness of the distribution of log agricultural output, we transform the dependent variable by an inverse hyperbolic sine function instead. The reduced form estimates, reported in Appendix Table D2, remain negative and statistically significant at a slightly smaller magnitude.

In Table 2.3, we estimate Equation 2.1 using variable for the intensity of the actual shock households experienced. This variable measures the number of desert locust swarms that hit a given enumeration area in 2014. An additional swarm slightly decreases subsistence crops' production, but the effect is imprecisely estimated and significant at 10% only when the full set of controls is included. However, all the coefficients have the expected negative sign.

We next turn to the effect of the desert locust shock on agricultural assets, household labour supply (both off- and on-farm) and meals consumed by household members. Again, we estimate models using the indicator for actual shock exposure ("Unadjusted"-headed columns), the "recentered" instrument ("Recentered"-headed columns), and by including a basic and a more comprehensive set of control variables. In Table B1, we do not find that livestock holdings are significantly different in *affected* areas, compared to *non affected* areas. All the estimated coefficients are very close to zero, suggest-

Table 2.2: Reduced-form effect of locust on agricultural output

	All crops (kg)				Subsistence crops (kg)			
	Unadjusted	Unadjusted	Recentered	Recentered	Unadjusted	Unadjusted	Recentered	Recentered
Affected	-0.480^{**}	-0.505^{**}	-0.526^{**}	-0.548^{**}	-0.545^{***}	-0.585^{***}	-0.591^{***}	-0.625^{***}
	(0.194)	(0.201)	(0.209)	(0.216)	(0.202)	(0.210)	(0.216)	(0.225)
Baseline outcome	0.555^{***}	0.450^{***}	0.556^{***}	0.451^{***}	0.456^{***}	0.365^{***}	0.456^{***}	0.365^{***}
	(0.039)	(0.040)	(0.039)	(0.040)	(0.060)	(0.058)	(0.060)	(0.058)
Control mean	4.762	4.762	4.762	4.762	3.761	3.761	3.761	3.761
Farm area	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
EA controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Household controls	No	Yes	No	Yes	No	Yes	No	Yes
Ethnicity FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
R^2	0.689	0.700	0.689	0.700	0.647	0.662	0.647	0.662
Num. obs.	2138	2062	2138	2062	2138	2062	2138	2062

Notes: *, **, and *** indicate significance at the 10%, 5%, and 1% levels. The outcomes are the logarithm of self-reported total agricultural output in wave 3 (columns 1 to 4) and the logarithm of self-reported agricultural output from subsistence crops in wave 3 (columns 5 to 8). Coefficients of the *Affected* variable in *unadjusted* models have been estimated using a binary indicator for actual shock exposure. Coefficients of the *Affected* variable in *recentered* models have been estimated using the "recentered" instrument. *Baseline outcome* controls for the level of the outcome in wave 2. *Control mean* shows the mean of the outcome in the *non affected* group. *Farm area* controls for the logarithm of total (subsistence) household cultivated area in wave 2. *EA controls* include precipitation (mm), temperature (C), vegetation indexes and humidity levels, measured in deviation from the historical average in wave 2, and an indicator variable for rural versus small town enumeration area. *Household controls* include the number of household members, age, sex, and religion of the household head, indicator variables for farm type, the logarithm of household expenses and total farm labour, all measured in wave 2.

ing that exposure to desert locust swarms did not cause disinvestment of agricultural assets (in the form of livestocks).

Off-farm household labour supply, measured in working days, is significantly higher in *affected* areas, compared to *non affected* ones, as shown in Table B2. *Affected* households supply between 57 and 77% more working days in off-farm activities. This is consistent with agricultural production becoming less profitable due to the exposure to the shock. However, we don't find that *affected* households substitute on-farm labour with off-farm labour, as the shock does not have a significant impact on the latter and the estimated coefficients are positive. This might suggest that the shock induced household members who were previously not working on the farm to enter non-agricultural labour markets, or that members who were already only employed in off-farm activities increased their labour supply. Again, the estimates are consistent when we use the "recentered" instrument as explanatory variable. Finally, the self-reported average number of meals consumed by adults and children is not different across *affected* and *non affected* communities as reported in Table B3.

We then explore the results on children's nutritional status measured as BMI z-score and weight-for-height z-score as reported in Table 2.4. The reduced form estimates show a negative, although non significant, effect, for all specifications. This indicates that, in our setting, being exposed to desert locust swarms does not affect children's

Table 2.3: Reduced-form effect of locust intensity on agricultural output

	All crops		Subsistence crops	
	kg	kg	kg	kg
Locusts intensity	−0.031	−0.039	−0.051	−0.060*
	(0.032)	(0.032)	(0.033)	(0.032)
Baseline outcome	0.557***	0.450***	0.465***	0.372***
	(0.039)	(0.041)	(0.060)	(0.059)
Control mean	4.762	4.762	3.761	3.761
Farm area	Yes	Yes	Yes	Yes
EA controls	Yes	Yes	Yes	Yes
Household controls	No	Yes	No	Yes
Ethnicity FE	Yes	Yes	Yes	Yes
R^2	0.688	0.699	0.646	0.661
Num. obs.	2138	2062	2138	2062

Notes: *, **, and *** indicate significance at the 10%, 5%, and 1% levels. The outcomes are the logarithm of self-reported total agricultural output in wave 3 (columns 1 and 2) and the logarithm of self-reported agricultural output from subsistence crops in wave 3 (columns 3 and 4). Coefficients of the *Locusts intensity* variable have been estimated using a discrete variable that indicates how many desert locust swarms hit a given enumeration area. *Baseline outcome* controls for the level of the outcome in wave 2. *Control mean* shows the mean of the outcome in the *non affected* group. *Farm area* controls for the logarithm of total (subsistence) household cultivated area in wave 2. *EA controls* include precipitation (mm), temperature (C), vegetation indexes and humidity levels, measured in deviation from the historical average in wave 2, and an indicator variable for rural versus small town enumeration area. *Household controls* include the number of household members, age, sex, and religion of the household head, indicator variables for farm type, the logarithm of household expenses and total farm labour, all measured in wave 2.

health. However, in Table 2.5, we show that the intensity of exposure does matter. One additional desert locust swarm is associated with a BMI z-score and a weight-for-height z-score for *affected* children that are 0.032 standard deviations (5.3%) and 0.031 standard deviations (5%) lower than for *non affected* children, respectively. If nutritional status decreases linearly with the shock intensity, at the median value of shock intensity we would see a worsening in BMI z-score and weight-for-age z-score equal to 0.096 and 0.093 standard deviations.

Overall, we find that a small-medium size desert locust outbreak significantly lowers agricultural output. The results are robust to the inclusion of several controls, as well as estimating the effect size using a "recentered" instrument similar to the one proposed in Borusyak and Hull (2021). We do find that *affected* households increase off-farm labour supply in response to the shock. Since livestock herd size is not impacted by the shock, in the context of rural Ethiopia, increasing off-farm labour supply

Table 2.4: Reduced-form effect of locust on children nutritional status

	BMI				WFH			
	Unadjasted	Unadjasted	Recentered	Recentered	Unadjasted	Unadjasted	Recentered	Recentered
Affected	-0.222	-0.208	-0.265	-0.233	-0.096	-0.069	-0.128	-0.083
	(0.193)	(0.174)	(0.209)	(0.188)	(0.187)	(0.167)	(0.203)	(0.181)
Baseline outcome	0.210^{***}	0.202^{***}	0.209^{***}	0.202^{***}	0.234^{***}	0.221^{***}	0.234^{***}	0.221^{***}
	(0.030)	(0.031)	(0.030)	(0.031)	(0.036)	(0.037)	(0.036)	(0.037)
Age	0.001	-0.002	0.001	-0.002	-0.007	-0.008	-0.007	-0.008
	(0.008)	(0.008)	(0.008)	(0.008)	(0.007)	(0.007)	(0.007)	(0.007)
Age^2	-0.000^{*}	-0.000	-0.000^{*}	-0.000	0.000	0.000	0.000	0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Female	-0.086	-0.096	-0.087	-0.096	-0.167^{**}	-0.172^{**}	-0.167^{**}	-0.172^{**}
	(0.074)	(0.076)	(0.074)	(0.076)	(0.074)	(0.075)	(0.074)	(0.075)
Control mean	-0.604	-0.604	-0.604	-0.604	-0.615	-0.615	-0.615	-0.615
EA controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Household controls	No	Yes	No	Yes	No	Yes	No	Yes
Mother controls	No	Yes	No	Yes	No	Yes	No	Yes
Ethnicity FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
R^2	0.179	0.208	0.179	0.209	0.133	0.160	0.133	0.160
Num. obs.	1459	1352	1459	1352	1459	1352	1459	1352

Notes: *, **, and *** indicate significance at the 10%, 5%, and 1% levels. The outcomes are BMI z-scores in wave 3 (columns 1 to 4) and weight-for-height z-scores (columns 5 to 8). Coefficients of the *Affected* variable in *unadjusted* models have been estimated using a binary indicator for actual shock exposure. Coefficients of the *Affected* variable in *recentered* models have been estimated using the "recentered" instrument. *Baseline outcome* controls for the level of the outcome in wave 2. *Control mean* shows the mean of the outcome in the *non affected* group. *EA controls* include precipitation (mm), temperature (C), vegetation indexes and humidity levels, measured in deviation from the historical average in wave 2, and an indicator variable for rural versus small town enumeration area. *Household controls* include age, sex, and religion of the household head, indicator variables for farm type, the logarithm of household expenses, all measured in wave 2. *Mother controls* include mother education, age and age squared, and an indicator for labour market participation, measured in wave 2.

Table 2.5: Reduced-form effect of locust intensity on children nutritional status

	BMI	BMI	WFH	WFH
Locusts intensity	-0.021^{*}	-0.032^{***}	-0.022^{*}	-0.031^{***}
	(0.013)	(0.012)	(0.011)	(0.011)
Baseline outcome	0.210^{***}	0.203^{***}	0.236^{***}	0.223^{***}
	(0.030)	(0.031)	(0.036)	(0.037)
Age	0.001	−0.002	−0.007	−0.009
	(0.008)	(0.008)	(0.007)	(0.007)
Age^2	-0.000^{*}	−0.000	0.000	0.000
	(0.000)	(0.000)	(0.000)	(0.000)
Female	−0.089	−0.099	-0.168^{**}	-0.173^{**}
	(0.074)	(0.075)	(0.074)	(0.075)
Specification	OLS	OLS	OLS	OLS
Control mean	−0.604	−0.604	−0.615	−0.615
EA controls	Yes	Yes	Yes	Yes
Household controls	No	Yes	No	Yes
Mother controls	No	Yes	No	Yes
Ethnicity FE	Yes	Yes	Yes	Yes
R^2	0.179	0.211	0.134	0.164
Num. obs.	1459	1352	1459	1352

Notes: *, **, and *** indicate significance at the 10%, 5%, and 1% levels. The outcomes are BMI z-scores in wave 3 (columns 1 and 2) and weight-for-height z-scores (columns 3 and 4). Coefficients of the *Locusts intensity* variable have been estimated using a discrete variable that indicates how many desert locust swarms hit a given enumeration area. *Baseline outcome* controls for the level of the outcome in wave 2. *Control mean* shows the mean of the outcome in the *non affected* group. *EA controls* include precipitation (mm), temperature (C), vegetation indexes and humidity levels, measured in deviation from the historical average in wave 2, and an indicator variable for rural versus small town enumeration area. *Household controls* include age, sex, and religion of the household head, indicator variables for farm type, the logarithm of household expenses, all measured in wave 2. *Mother controls* include mother education, age and age squared, and an indicator for labour market participation, measured in wave 2.

can represent a viable, and preferred to the liquidation of agricultural assets, way to smooth consumption in the aftermath of a negative agricultural shock. Moreover, the additional income resulting from increased labour supply might have balanced the loss of income resulting from the reduction in agricultural production, shielding children from adverse health consequences.

The lack of an average effect on the nutritional status of children who were not exposed to desert locust shocks after birth is consistent with the results of Conte et al. (2021) in Mali. Similarly, we do not find a male-female differential effect in our sample. This is reassuring, as in two very different contexts preferences do not seem to skew distribution of resources during crisis towards one or the other sex. However, our findings show that the intensity of the shock matters: a marginal increase in the shock severity (measured by one additional swarm affecting one enumeration area) leads to a worsening of children nutritional status. Because of this and the fact that in Conte et al. (2021) the number of swarms is larger, compared to our setting, it can not be excluded that in the presence of larger outbreaks (or plagues) children's health would be more severely affected. We also find evidence that the shock persists: agricultural production is lowered up to two agricultural seasons after the shock hits. Although we can not disentangle the channel for this persistence, this is consistent with Bekar (2019) findings that harvests are not self-contained.

2.5.2 Heterogeneity

We explore two potential sources of heterogeneity. For children nutritional status, we study how the effect of desert locusts varies along gender and birth order dimensions. Parents' preferences can skew the allocation of resources towards male or female children, as well as towards first born children. Parents' preferences for males versus females can be important when resources are scarce or when the household faces a crisis (Duflo, 2012). Similarly, parents can favour first-borns over children born later, especially in those situations where the first-born is expected to inherit family land (Jayachandran and Pande, 2017).

In Figure 2.4a, we look at heterogeneity with respect to child biological sex. Both male and female *affected* children present nutritional score that are worse, on average, than their *non affected* counterparts. However, in both *affected* and *non affected* areas, male children's z-scores do not seem to be different than female ones. We confirm this empirically, by interacting the *affected* variable with a variable that indicates whether the child is female (Table B4). We find that female children are not disproportionately affected by the desert locust shock, compared to males. The coefficient on the interaction is small and non significant in each of the specifications we consider.

In Figure 2.4b, we show the average wave 3 BMI z-score and weight-for-height z-score for *affected* and *non affected* children by birth order. When looking at raw averages, we see that first-born children in *affected* households present significantly (10%) worse BMI z-scores than first-born children in *non affected* households. However, weight-for-age z-scores do not seem to differ across *affected* and *non affected* areas for first-born children. Later-born children in *affected* and *non affected* households are not different. Later-born children in *affected* areas have significantly better BMI and weight-for-height z-scores compared to their older siblings, while for later-borns in *non affected* areas only BMI z-score is significantly better than that of first-borns.

In Table B5, we estimate Equation 2.2 including an indicator for later-born children and its interaction with the *affected* variable. When looking at BMI, first-born children in *affected* areas have lower z-scores than first-borns in *non affected* ones. However, the coefficients are significant at 10% only when the "recentered" indicator is used. Later-borns present better nutritional status than first-borns in *affected* areas, as captured by the positive interaction coefficient, but the effect is only marginally significant when the smaller set of control variables is used. The picture is similar when looking at weight-for-height z-scores. If children nutritional status is a direct consequence parents' preferences in resources allocation, it does not seem that first-borns are generally allocated more resources in time of crisis. However, we are not able to disentangle whether better nutritional status of younger siblings is due to allocation of resources or to the fact that older siblings might have been exposed longer to harsher conditions.

2.6 Conclusions

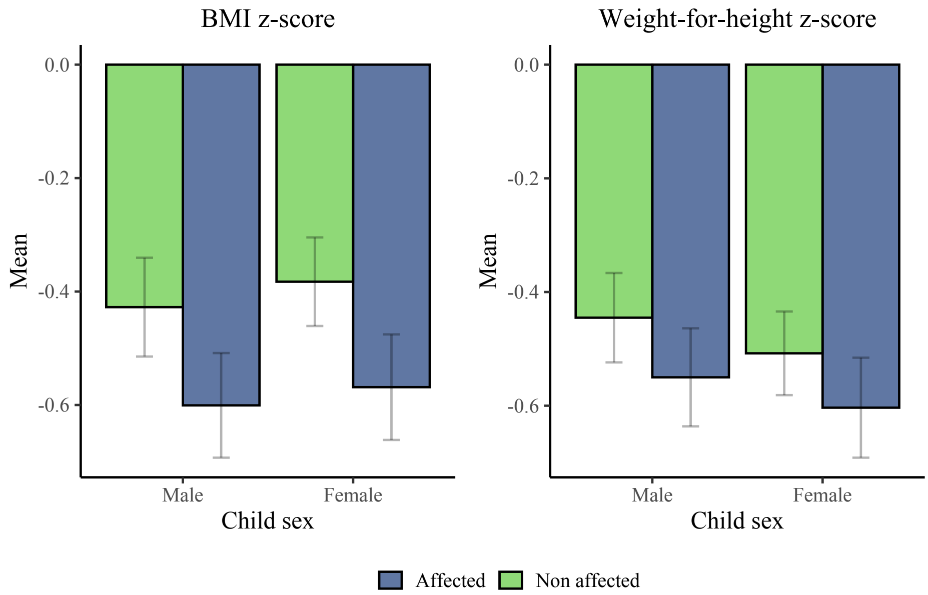
In this paper, we study the effect of a desert locusts outbreak in Ethiopia on agricultural output and children nutritional status. We identify the causal effect of the outbreak by predicting which areas are *affected* or *non affected* by desert locust swarms by means of NOAA's HYSPLIT model, commonly used to predict dispersion of particles in the atmosphere. Because the predicted position depends on wind speed and direction, it is exogenous to farm household preferences. We finally compare measures of agricultural output, labour supply, resource allocation and children nutritional status across *affected* and *non affected* areas.

First, we show that after the shock, *affected* households produce lower quantities of crops on their fields, compared to *non affected* households. Agricultural output is about 10% lower in *affected* areas. We do not find that livestock holdings are affected by the shock. However, *affected* households have higher off-farm labour supply, compared to *non affected* ones. This is consistent with households coping with the shock by increasing off-farm labour supply, whose returns are now higher compared to on-farm labour and not by liquidating agricultural assets. Next, we show that desert locusts does have a direct effect on children nutritional status on average, but the magnitude of the effect is increasing in the shock severity. We do not find that female children are disproportionately hit, compared to male children, but first-borns might bear larger negative consequences than their younger siblings.

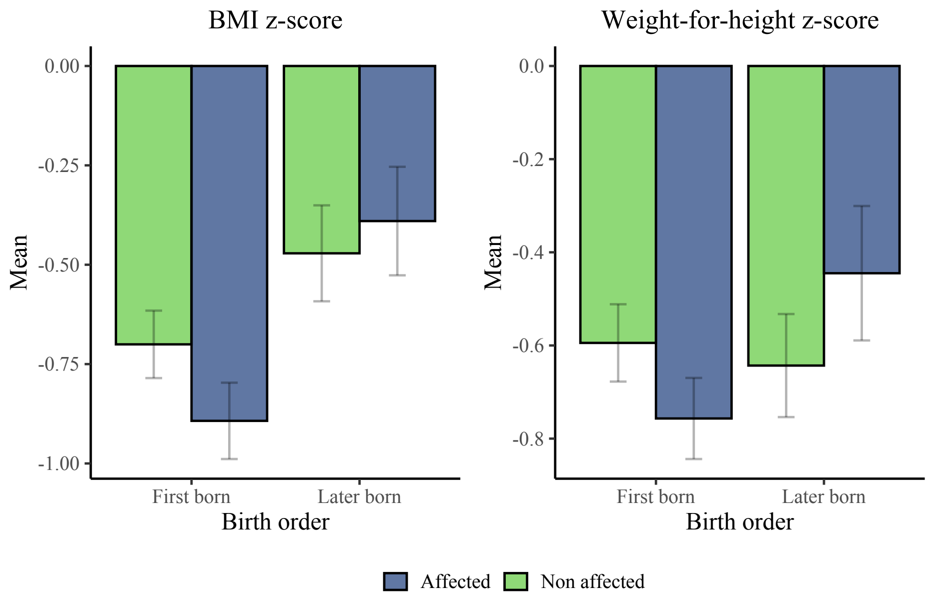
Our results are robust to an alternative estimation strategy, namely the use of a "recentered" instrument, calculated by simulating desert locust flight trajectory had they happen during the 15 years previous the actual shock, and by subtracting from the actual shock exposure variable the average number of times an enumeration areas have been hit by the simulated swarms. This approach removes bias arising from non-exogenous determinants of shock exposure, such as historic settlement decisions.

Figure 2.4: Heterogeneity children's anthropometric outcome

(a) Wave 3 children's anthropometric outcome by *affected* status and child sex



(b) Wave 3 children's anthropometric outcome by *affected* status and birth order



Notes: This figure shows BMI and weight-for-height z-scores averages in wave 3 by child biological sex (Panel (A)) and birth order (Panel (B)), across *affected* and *non affected* statuses. Birth order equal to 1 means that the child is the first born; birth order equal to 2 means that the child is a later-born. 90% confidence bands on top of bars.

of our knowledge, to apply meteorological models to predict the location of desert locusts and to use the resulting predicted positions to quantify the economic and welfare consequences of infestations. Based on our findings and the significant implied productivity losses due to desert locust outbreaks, the focus should be primarily on ex ante prevention mechanisms. This includes climate change mitigation policies to minimise environmental factors that favour locust breeding and spreading, such as abnormal rains. Furthermore, along the work of the FAO, monitoring and control measures should be implemented. The public availability of the Locust Hub dataset as well as the monthly publication of the Locust Bulletin by the FAO is a milestone in this direction. The reported results furthermore stress the relevance of ex post recovery programs for *affected* communities, particularly in lieu of the persistence of the shock's impact.

APPENDIX

This Supplementary Material appendix provides greater detail on data sources, variables and methods used in this chapter (Appendix Section A), and summarizes findings from additional analyses (Appendix Section B).

A Data and methodological procedures

A.1 Variables and data sources

The following table presents a description of the variables used in this chapter.

Variable (Source)	Description
Administrative divisions (GADM)	The data on national and subnational administrative divisions is from GADM version 3.6, released in 2018, which can be accessed at [https://gadm.org].
Child characteristics (LSMS)	Data on child characteristics are taken from the Household Module of the LSMS survey. We calculate age in months as the difference between survey date and birth date. Height and weight are the result of measurements taken by the Field Officers. Anthropometric measures are computed in Stata using the extension to the `egen()` function `zanthro()` (Vidmar et al., 2004). In order to calculate z-scores, we supply to the function child weight, height, age in months and sex. Z-scores are then standardised to the WHO reference population.
Desert locust swarms (FAO Locust Hub)	Data are publicly available at https://locust-hub-hqfao.hub.arcgis.com. A field team records the GPS coordinates and timing of the event using a touch-screen handheld data logger (*eLocust3*) and sends the information to the National Locust Control Center for analysis, which uses the information to forecast and backcast locust movements and to create early warnings for areas potentially affected.
Ethnicity (Ethnographic Atlas Murdock)	Historic borders of ethnicities' homelands are taken from https://github.com/sboysel/murdock, which provides the Murdock (1959) ethnolinguistic map for the African continent as a `SpatialPolygonDataFrame`. This is a repackaging of the original data, attributed to George Murdock, Suzanne Blier and Nathan Nunn.

(continued on next page)

Variable (Source)	Description
Household characteristics (LSMS)	Household characteristics are taken from various Modules of the LSMS survey. Household members demographic characteristics (household head and mothers) are taken from the Household Module, which collect demographic information for each household member. Labour force participation information are taken from the same Module. We define labour force participation as participation to either the formal or the informal labour market sector in the 12 months before the survey. Total household off-farm labour is calculated as the household-level total number of working days worked by a household member in the last 12 months. It includes days worked in formal and informal labour market. Farm area data are taken from the Post-Planting Module. We define total farm area and total subsistence farm area as the household-level total area cultivated with any crop and with subsistence crops, respectively. Agricultural output data are taken from the Post-Harvest Module. We define total and subsistence output as the household-level sum of agricultural production from any and subsistence crops, respectively. Livestock holdings information come from the Livestock Module. We calculate total household livestock holdings in Tropical Livestock Units, as described in Njuki et al. (2011). Data about household and non-household labour on household plots come from both the Post-Planting and Post-Harvest modules. We calculate household labour as the total of household members supplied working days on each plot and non-household labour as the total of non household members supplied working days. Consumption expenditures information are taken from the Consumption Aggregate Module.
Humidity (ERA5-Land)	Gridded data at 0.1×0.1 degrees latitude-longitude intersected with the locations of the enumeration areas. Humidity is defined as the accumulated amount of water that has evaporated from the Earth's surface into vapour in the air above, it is measured in meters of water equivalent. The values are coded such that negative values indicate evaporation and positive values indicate condensation. We use the deviations from historical, 30 years, average levels. The data is from ERA5-Land monthly reanalysis dataset, (1981-present) Sabater (2019).
Precipitation (ERA5-Land)	Gridded data at 0.1×0.1 degrees latitude-longitude intersected with the locations of the enumeration areas. Calculated as deviations from historical, 30 years, averages of precipitation levels measured at accumulated liquid water that falls to the surface quantified in units of depth in metres, i.e. the average depth the water would have measured were it spread evenly over the grid box of 0.1×0.1 degrees latitude-longitude. The data is from ERA5-Land monthly reanalysis dataset, (1981-present) Sabater (2019).
Temperature (ERA5-Land)	Gridded data at 0.1×0.1 degrees latitude-longitude intersected with the locations of the enumeration areas. Calculated as deviations from historical, 30 years, averages of temperature levels measured as mean yearly temperature in degrees Celsius. The data is from ERA5-Land monthly reanalysis dataset, (1981-present) Sabater (2019), and converted from kelvin to degrees Celsius by subtracting 273.15.
Vegetation indices (ERA5-Land)	Gridded data at 0.1×0.1 degrees latitude-longitude intersected with the locations of the enumeration areas. The leaf indices measure the total green leaf area per ground surface area, separately accounting for high and low vegetation type ($m^2 m^{-2}$). The data is from ERA5-Land monthly reanalysis dataset, (1981-present) Sabater (2019).

Notes:

A.2 Children attrition

In wave 3, a total of 346 children that were part of participating households in wave 2 could not be interviewed. In Table A2, we check whether there is differential attrition across *Affected* and *non affected* areas. We don't find evidence of selective attrition.

Table A2: Attrition across *Affected* and *Non affected* areas

	Child attrited	Child attrited
Affected	-0.041	-0.062
	(0.044)	(0.041)
Control mean	0.201	0.201
EA controls	Yes	Yes
Child controls	No	Yes
Mother controls	No	Yes
Household controls	No	Yes
Ethnicity FE	Yes	Yes
R^2	0.044	0.109
Num. obs.	1717	1664

Notes: *, **, and *** indicate significance at the 10%, 5%, and 1% levels.

A.3 Missing values imputation

Our main outcome variables, children nutritional status in wave 3, present some missing values. These missing values are due to the fact that, given parameters on age, weight and height, calculation of z-score was not possible. Table A3 shows that BMI z-score is not more likely to be missing for children living in *Affected* areas, while weight-for-height z-score is marginally more likely to be missing.

We handle these missing information by predicting missing values using a random forest algorithm. We predict missing values using a large set of predictors, which include children, household and enumeration areas covariates. We choose the number of predictors to be used at each split of the tree via 10-fold cross validation.

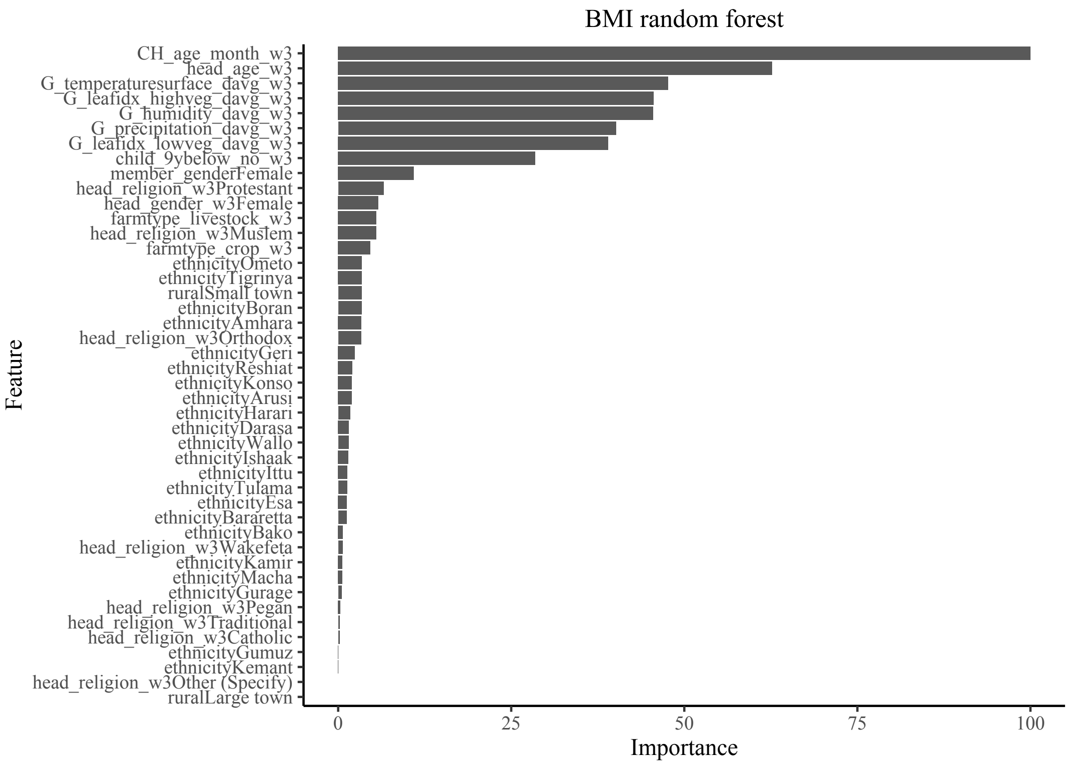
For both outcomes, these predictors are able to explain about 16% of outcome variance. In Figure A1 and A2, we plot the most important predictors for BMI z-score and weight-for-height z-score, respectively, on a scale from 0 to 100 (where 0 means not important and 100 is assigned to the most relevant variable). In both cases, the most important predictor is child age in month. Meteorological variables are also relatively important, while ethnicity does not seem to play an important role. In all our empirical specifications, we include a indicator variable equal to 1 in case a replacement for missing values took place.

Table A3: Prevalence of missing values across *Affected* and *Non affected* areas

	BMI	WFH
Affected	0.031	0.071^{*}
	(0.021)	(0.037)
Control mean	0.029	0.135
EA controls	Yes	Yes
Child controls	Yes	Yes
Ethnicity FE	Yes	Yes
R^2	0.027	0.236
Num. obs.	1459	1459

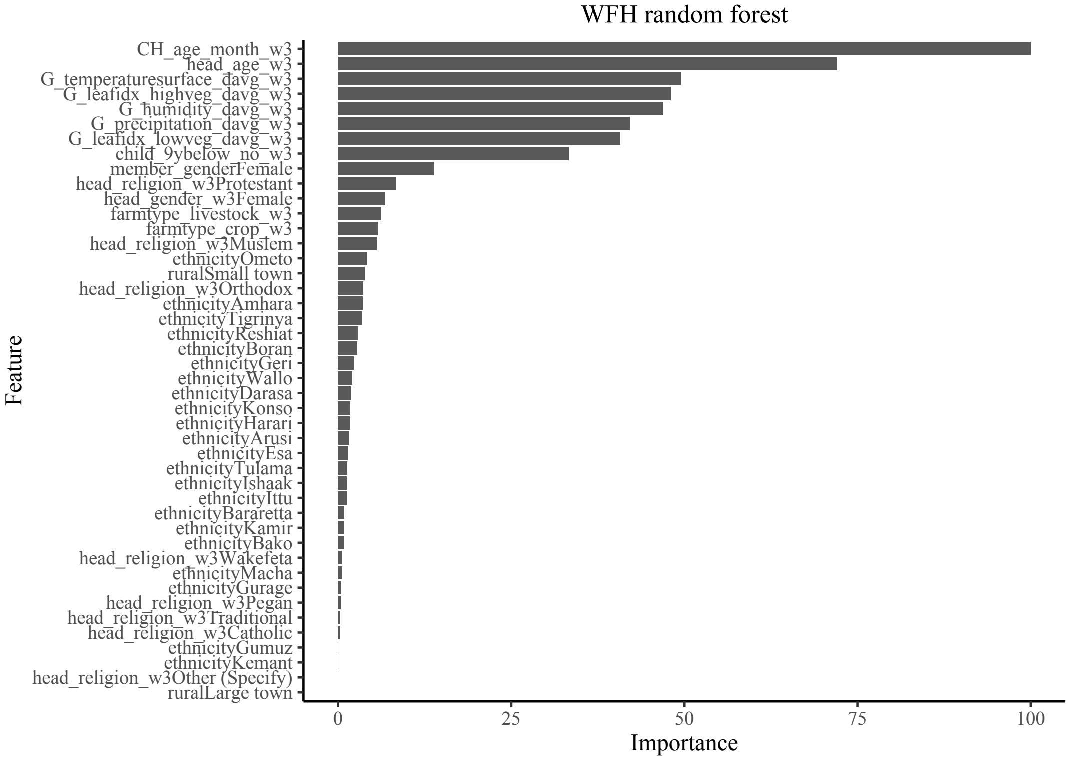
$^{***}p < 0.01$; $^{**}p < 0.05$; $^{*}p < 0.1$. Robust standard errors clustered at the enumeration area level in parentheses. The outcomes are indicator variables eaqual to 1 if BMI z-scores of weight-for-height z-score are missing in wave 3, respectively. BMI indicates body mass index z-score; WFH indicates weight-for-height z-score. The explanatory variable *Affected* is an indicator equal to one if the enumeration area was affected by desert locus swarms in wave 3.

Figure A1: Relative variable importance for BMI z-score random forest prediction



We do not have missing values for relevant covariates, except for mother labour market participation and education (3 observations). We impute both as 0, as we believe this is the most conservative approach.

Figure A2: Relative variable importance for weight-for-height z-score random forest prediction



B Supplementary results

Table B1: Reduced-form effect of locust on livestock holdings

	Livestock (TLU)			
	Unadjusted	Unadjusted	Recentered	Recentered
Affected	0.043	0.121	0.115	0.183
	(0.470)	(0.433)	(0.545)	(0.497)
Baseline outcome	0.582***	0.536***	0.582***	0.536***
	(0.075)	(0.085)	(0.076)	(0.086)
Control mean	6.568	6.568	6.568	6.568
EA controls	Yes	Yes	Yes	Yes
Household controls	No	Yes	No	Yes
Ethnicity FE	Yes	Yes	Yes	Yes
R^2	0.086	0.553	0.086	0.553
Num. obs.	2138	2062	2138	2062

Notes: *, **, and *** indicate significance at the 10%, 5%, and 1% levels. The outcomes are herd size in Tropical Livestock Units (TLUs). Coefficients of the *Affected* variable in *unadjusted* models have been estimated using a binary indicator for actual shock exposure. Coefficients of the *Affected* variable in *recentered* models have been estimated using the "recentered" instrument. *Baseline outcome* controls for the level of the outcome in wave 2. *Control mean* shows the mean of the outcome in the *non affected* group. *Main controls* include the logarithm of total (subsistence) household cultivated area in wave 2. *EA controls* include precipitation (mm), temperature (C), vegetation indexes and humidity levels, measured in deviation from the historical average in wave 2, and an indicator variable for rural versus small town enumeration area. *Household controls* include the number of household members, age, sex, and religion of the household head, indicator variables for farm type, the logarithm of household expenses and total farm labour, all measured in wave 2.

Table B2: Reduced-form effect of household labour days

	Off-farm labour days				On-farm labour days			
	Unadjusted	Unadjusted	Recentered	Recentered	Unadjusted	Unadjusted	Recentered	Recentered
Affected	16.066***	13.670**	18.417***	15.685**	23.632	21.899	39.573	35.556
	(5.600)	(5.783)	(6.440)	(6.504)	(69.400)	(67.706)	(74.107)	(72.057)
Baseline outcome	0.385***	0.372***	0.385***	0.372***	0.465***	0.430***	0.465***	0.431***
	(0.052)	(0.053)	(0.052)	(0.053)	(0.075)	(0.083)	(0.075)	(0.083)
Control mean	23.711	23.711	23.711	23.711	377.163	377.163	377.163	377.163
Farm area	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
EA controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Household controls	No	Yes	No	Yes	No	Yes	No	Yes
Ethnicity FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
R^2	0.212	0.226	0.212	0.226	0.340	0.356	0.340	0.356
Num. obs.	2109	2041	2109	2041	2138	2062	2138	2062

Notes: *, **, and *** indicate significance at the 10%, 5%, and 1% levels. The outcomes are the total household off-farm labour days in wave 3 (columns 1 to 4) and total household on-farm labour days in wave 3 (columns 5 to 8). Coefficients of the *Affected* variable in *unadjusted* models have been estimated using a binary indicator for actual shock exposure. Coefficients of the *Affected* variable in *recentered* models have been estimated using the "recentered" instrument. *Baseline outcome* controls for the level of the outcome in wave 2. *Control mean* shows the mean of the outcome in the *non affected* group. *Farm area* controls for the logarithm of total household cultivated area in wave 2. *EA controls* include precipitation (mm), temperature (C), vegetation indexes and humidity levels, measured in deviation from the historical average in wave 2, and an indicator variable for rural versus small town enumeration area. *Household controls* include the number of household members, age, sex, and religion of the household head, indicator variables for farm type, and the logarithm of household expenses, all measured in wave 2.

Table B3: Reduced-form effect of meals consumed by household members

	Daily meals $<$ 5 years old				Daily meals $\geq$ 5 years old			
	Unadjusted	Unadjusted	Recentered	Recentered	Unadjusted	Unadjusted	Recentered	Recentered
Affected	0.021	0.005	−0.016	−0.038	0.078	0.067	0.085	0.071
	(0.153)	(0.152)	(0.172)	(0.168)	(0.055)	(0.055)	(0.062)	(0.062)
Baseline outcome	0.070**	0.053*	0.070**	0.053*	0.077***	0.067***	0.077***	0.067***
	(0.028)	(0.029)	(0.028)	(0.029)	(0.022)	(0.023)	(0.023)	(0.023)
Control mean	3.822	3.822	3.822	3.822	2.867	2.867	2.867	2.867
EA controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Household controls	No	Yes	No	Yes	No	Yes	No	Yes
Ethnicity FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
R^2	0.210	0.242	0.210	0.242	0.175	0.203	0.175	0.203
Num. obs.	953	914	953	914	2101	2033	2101	2033

Notes: *, **, and *** indicate significance at the 10%, 5%, and 1% levels. The outcomes are the average number of meals received daily in the last 7 days by children (less than 5 years old) in wave 3 (columns 1 to 4) and the average number of meals received daily in the last 7 days by adults (older than 5 years old) (columns 5 to 8). Coefficients of the *Affected* variable in *unadjusted* models have been estimated using a binary indicator for actual shock exposure. Coefficients of the *Affected* variable in *recentered* models have been estimated using the "recentered" instrument. *Baseline outcome* controls for the level of the outcome in wave 2. *Control mean* shows the mean of the outcome in the *non affected* group. *EA controls* include precipitation (mm), temperature (C), vegetation indexes and humidity levels, measured in deviation from the historical average in wave 2, and an indicator variable for rural versus small town enumeration area. *Household controls* include age, sex, and religion of the household head, indicator variables for farm type, the logarithm of household expenses, the logarithm of agricultural output and the number of children (adults) in the household, all measured in wave 2.

Table B4: Reduced-form effect of locust on children nutritional status by child biological sex

	BMI				WFH			
	Unadjasted	Unadjasted	Recentered	Recentered	Unadjasted	Unadjasted	Recentered	Recentered
Affected	−0.194	−0.192	−0.254	−0.238	−0.080	−0.074	−0.130	−0.110
	(0.211)	(0.191)	(0.233)	(0.210)	(0.205)	(0.186)	(0.226)	(0.202)
Affected × Female	−0.061	−0.034	−0.024	0.010	−0.033	0.010	0.005	0.056
	(0.139)	(0.143)	(0.169)	(0.172)	(0.140)	(0.144)	(0.169)	(0.172)
Baseline outcome	0.209***	0.202***	0.209***	0.202***	0.234***	0.221***	0.234***	0.221***
	(0.030)	(0.031)	(0.030)	(0.031)	(0.036)	(0.037)	(0.036)	(0.037)
Age	0.001	−0.002	0.001	−0.002	−0.007	−0.008	−0.007	−0.008
	(0.008)	(0.008)	(0.008)	(0.008)	(0.007)	(0.007)	(0.007)	(0.007)
Age^2	−0.000*	−0.000	−0.000*	−0.000	0.000	0.000	0.000	0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Female	−0.062	−0.082	−0.080	−0.099	−0.154	−0.176*	−0.168*	−0.189*
	(0.104)	(0.107)	(0.099)	(0.102)	(0.101)	(0.104)	(0.096)	(0.099)
Control mean	−0.427	−0.427	−0.427	−0.427	−0.549	−0.549	−0.549	−0.549
EA controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Household controls	No	Yes	No	Yes	No	Yes	No	Yes
Mother controls	No	Yes	No	Yes	No	Yes	No	Yes
Ethnicity FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
R^2	0.179	0.208	0.179	0.209	0.133	0.160	0.133	0.160
Num. obs.	1459	1352	1459	1352	1459	1352	1459	1352

Notes: *, **, and *** indicate significance at the 10%, 5%, and 1% levels. The outcomes are BMI z-scores in wave 3 (columns 1 to 4) and weight-for-height z-scores (columns 5 to 8). Coefficients of the *Affected* variable in *unadjusted* models have been estimated using a binary indicator for actual shock exposure. Coefficients of the *Affected* variable in *recentered* models have been estimated using the "recentered" instrument. *Baseline outcome* controls for the level of the outcome in wave 2. *Control mean* shows the mean of the outcome in the *non affected* group. *EA controls* include precipitation (mm), temperature (C), vegetation indexes and humidity levels, measured in deviation from the historical average in wave 2, and an indicator variable for rural versus small town enumeration area. *Household controls* include age, sex, and religion of the household head, indicator variables for farm type, the logarithm of household expenses, all measured in wave 2. *Mother controls* include mother education, age and age squared, and an indicator for labour market participation, measured in wave 2.

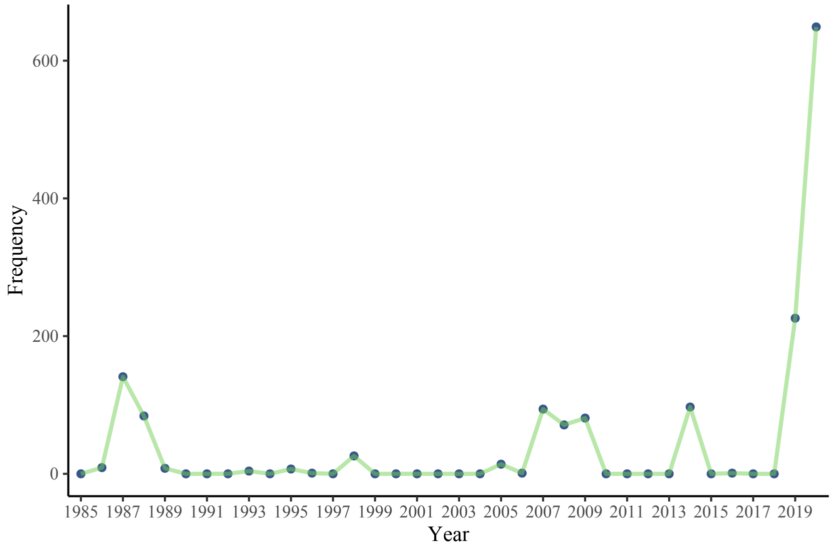
Table B5: Reduced-form effect of locust on children nutritional status by child birth order

	BMI				WFH			
	Unadjasted	Unadjasted	Recentered	Recentered	Unadjasted	Unadjasted	Recentered	Recentered
Affected	-0.315	-0.295	-0.380^{*}	-0.340^{*}	-0.210	-0.183	-0.271	-0.224
	(0.202)	(0.180)	(0.220)	(0.196)	(0.195)	(0.174)	(0.214)	(0.189)
Affected × Later born	0.273^{*}	0.245	0.335^{*}	0.300	0.333^{**}	0.317^{**}	0.415^{**}	0.392^{**}
	(0.146)	(0.152)	(0.187)	(0.194)	(0.142)	(0.151)	(0.182)	(0.192)
Later born	-0.163	-0.136	-0.149	-0.123	-0.189^{*}	-0.168	-0.175^{*}	-0.153
	(0.104)	(0.120)	(0.101)	(0.115)	(0.102)	(0.117)	(0.099)	(0.112)
Baseline outcome	0.209^{***}	0.202^{***}	0.209^{***}	0.202^{***}	0.233^{***}	0.220^{***}	0.232^{***}	0.220^{***}
	(0.030)	(0.031)	(0.030)	(0.031)	(0.036)	(0.037)	(0.036)	(0.037)
Age	0.000	-0.003	0.000	-0.003	-0.008	-0.009	-0.008	-0.009
	(0.008)	(0.008)	(0.008)	(0.008)	(0.007)	(0.007)	(0.007)	(0.007)
Age^2	-0.000^{*}	-0.000	-0.000^{*}	-0.000	0.000	0.000	0.000	0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Female	-0.084	-0.092	-0.084	-0.093	-0.163^{**}	-0.167^{**}	-0.163^{**}	-0.167^{**}
	(0.073)	(0.075)	(0.073)	(0.075)	(0.073)	(0.074)	(0.072)	(0.074)
Control mean	-0.700	-0.700	-0.700	-0.700	-0.655	-0.655	-0.655	-0.655
EA controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Household controls	No	Yes	No	Yes	No	Yes	No	Yes
Mother controls	No	Yes	No	Yes	No	Yes	No	Yes
Ethnicity FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
R^2	0.181	0.210	0.182	0.210	0.137	0.163	0.137	0.163
Num. obs.	1459	1352	1459	1352	1459	1352	1459	1352

Notes: *, **, and *** indicate significance at the 10%, 5%, and 1% levels. The outcomes are BMI z-scores in wave 3 (columns 1 to 4) and weight-for-height z-scores (columns 5 to 8). Coefficients of the *Affected* variable in *unadjusted* models have been estimated using a binary indicator for actual shock exposure. Coefficients of the *Affected* variable in *recentered* models have been estimated using the "recentered" instrument. *Later born* is an indicator variable indicating that the child is not the first born in the household. *Baseline outcome* controls for the level of the outcome in wave 2. *Control mean* shows the mean of the outcome in the *non affected* group. *EA controls* include precipitation (mm), temperature (C), vegetation indexes and humidity levels, measured in deviation from the historical average in wave 2, and an indicator variable for rural versus small town enumeration area. *Household controls* include age, sex, and religion of the household head, indicator variables for farm type, the logarithm of household expenses, all measured in wave 2. *Mother controls* include mother education, age and age squared, and an indicator for labour market participation, measured in wave 2.

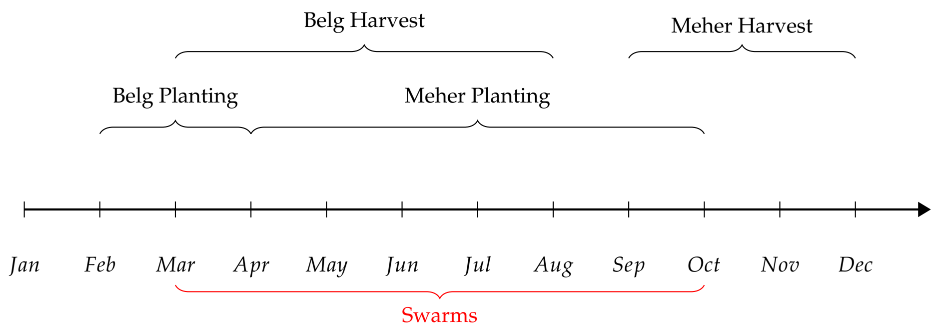
C Additional figures

Figure C1: Number of desert locust swarm events in Ethiopia between 1995 and 2020



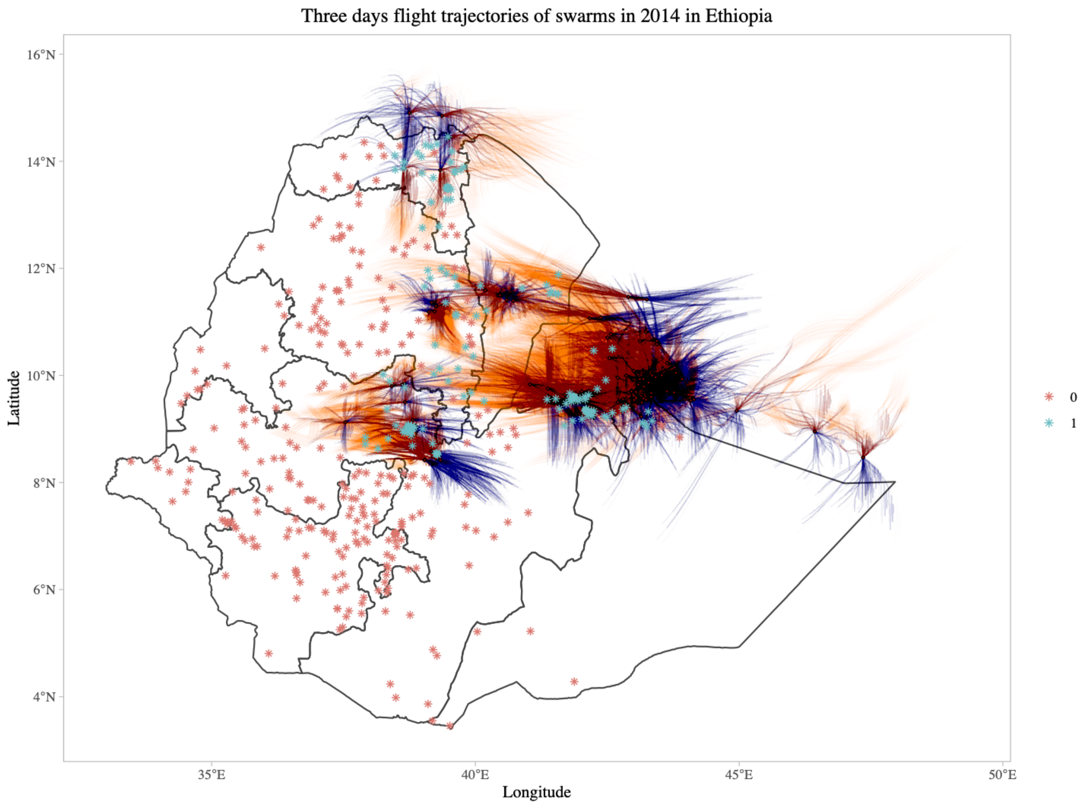
Notes: This figure shows the time series of all desert locust swarms reported in Ethiopia from 1985 to 2020.

Figure C2: Locusts events and agricultural seasons



Notes: This figure shows planting and harvesting timing in Ethiopia, as well as the period of exposure to locust swarms.

Figure C3: Three days trajectories of all desert locust swarms in 2014



Notes: This figure shows all forecasted and backcasted desert locust swarm trajectories in Ethiopia in 2014, as well as the categorization of each enumeration area into *Affected* and *non affected* status.

D Robustness checks

Table D1: Reduced-form effect of locust on agricultural output

	All crops (BIRR)				Subsistence crops (BIRR)			
	Unadjusted	Unadjusted	Recentered	Recentered	Unadjusted	Unadjusted	Recentered	Recentered
Affected	-0.591^{**}	-0.609^{**}	-0.662^{**}	-0.672^{**}	-0.687^{***}	-0.720^{***}	-0.745^{***}	-0.770^{***}
	(0.246)	(0.260)	(0.266)	(0.282)	(0.254)	(0.265)	(0.275)	(0.289)
Baseline outcome	0.612^{***}	0.552^{***}	0.612^{***}	0.553^{***}	0.530^{***}	0.490^{***}	0.530^{***}	0.490^{***}
	(0.038)	(0.042)	(0.038)	(0.042)	(0.058)	(0.057)	(0.058)	(0.057)
Control mean	5.474	5.474	5.474	5.474	4.463	4.463	4.463	4.463
EA controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Household controls	No	Yes	No	Yes	No	Yes	No	Yes
Ethnicity FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
R^2	0.678	0.688	0.679	0.688	0.636	0.645	0.636	0.645
Num. obs.	2138	2062	2138	2062	2138	2062	2138	2062

Notes: *, **, and *** indicate significance at the 10%, 5%, and 1% levels. The outcomes are the logarithm of total agricultural output value (in BIRR) in wave 3 (columns 1 to 4) and the logarithm of the value (in BIRR) of agricultural output from subsistence crops in wave 3 (columns 5 to 8). Coefficients of the *Affected* variable in *unadjusted* models have been estimated using a binary indicator for actual shock exposure. Coefficients of the *Affected* variable in *recentered* models have been estimated using the "recentered" instrument. *Baseline outcome* controls for the level of the outcome in wave 2. *Control mean* shows the mean of the outcome in the *non affected* group. *Farm area* controls for the logarithm of total (subsistence) household cultivated area in wave 2. *EA controls* include precipitation (mm), temperature (C), vegetation indexes and humidity levels, measured in deviation from the historical average in wave 2, and an indicator variable for rural versus small town enumeration area. *Household controls* include the number of household members, age, sex, and religion of the household head, indicator variables for farm type, the logarithm of household expenses and total farm labour, all measured in wave 2. Outcomes and baseline outcomes are priced using wave 3 market prices at the enumeration area level.

Table D2: Reduced form effect of locust on agricultural output (inverse hyperbolic sine transformation)

	All crops (kg)				Subsistence crops (kg)			
	Unadjusted	Unadjusted	Recentered	Recentered	Unadjusted	Unadjusted	Recentered	Recentered
Affected	-0.527^{**}	-0.554^{**}	-0.580^{**}	-0.604^{**}	-0.603^{***}	-0.646^{***}	-0.656^{***}	-0.693^{***}
	(0.210)	(0.218)	(0.226)	(0.234)	(0.219)	(0.228)	(0.234)	(0.244)
Baseline outcome	0.549^{***}	0.444^{***}	0.550^{***}	0.445^{***}	0.428^{***}	0.341^{***}	0.428^{***}	0.341^{***}
	(0.039)	(0.041)	(0.039)	(0.041)	(0.061)	(0.059)	(0.061)	(0.058)
Control mean	4.762	4.762	4.762	4.762	3.761	3.761	3.761	3.761
EA controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Household controls	No	Yes	No	Yes	No	Yes	No	Yes
Ethnicity FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
R^2	0.690	0.701	0.690	0.701	0.645	0.659	0.645	0.659
Num. obs.	2138	2062	2138	2062	2138	2062	2138	2062

Notes: *, **, and *** indicate significance at the 10%, 5%, and 1% levels. The outcomes are the inverse hyperbolic sine transformation of self-reported total agricultural output in wave 3 (columns 1 to 4) and of self-reported agricultural output from subsistence crops in wave 3 (columns 5 to 8). Coefficients of the *Affected* variable in *unadjusted* models have been estimated using a binary indicator for actual shock exposure. Coefficients of the *Affected* variable in *recentered* models have been estimated using the "recentered" instrument. *Baseline outcome* controls for the level of the outcome in wave 2. *Control mean* shows the mean of the outcome in the *non affected* group. *Farm area* controls for the logarithm of total (subsistence) household cultivated area in wave 2. *EA controls* include precipitation (mm), temperature (C), vegetation indexes and humidity levels, measured in deviation from the historical average in wave 2, and an indicator variable for rural versus small town enumeration area. *Household controls* include the number of household members, age, sex, and religion of the household head, indicator variables for farm type, the logarithm of household expenses and total farm labour, all measured in wave 2.

Chapter 3

Financial deepening and the informal economy: evidence from local credit cycles in India

Joint with Gabriel Züllig

3. Financial deepening and the informal economy: Evidence from local credit cycles in India

*Joint with Gabriel Züllig**

Summary

We analyse the role of formal credit on the size and dynamics of the shadow economy in India, an economy with a large informal sector and large cross-sectional and time heterogeneity in bank credit availability. We use district-level bank lending data from the Reserve Bank of India from 1997 to 2018 and measure light emissions observed from outer space at night time to proxy for economic activity. The identification strategy relies on the importance of gold as a collateral commodity for credit in India. We find that gold price fluctuations have a significantly expanding effect on credit supply. Credit supply expansions lead to growth of formal GDP (with a structural elasticity between 0.1 and 0.2). According to our estimates, resources are re-allocated from the informal to the formal sector. In the short run, the contraction of the informal sector is so strong that economic output as a whole tends to fall. The economy reaps the benefits of formalization after credit becomes more easily available only over the course of 3-5 years.

3.1 Introduction

How does the availability of credit affect the degree of formalization in a developing economy? Access to financing is the single-most named obstacle for firms to produce, and almost twice as important for informal compared to formal firms (La Porta and Shleifer, 2014). Granting a household or firm access to bank credit will allow them to invest and grow. At the same time, they will need to formally declare assets or income to be eligible for credit, potentially nudging them to formalize operations that were previously kept in the shadow. Increasing financial development and more efficient financial intermediation might therefore reduce the opportunity cost to operate in the

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shadow economy without access to external finance. Informal firms account for a large share of economic activity and provide livelihood for billions of people worldwide.

This paper examines to what extent the positive effects of access to credit on formal output found in the literature (Calderón and Liu, 2003) is simply a matter of reallocation of resources to the formal economy or whether it represents an increase of total economic activity. The question is answered using data from India, a country with a considerable shadow economy, estimated at 23 to 46% of official GDP on average with a large share of employment,[1] and sizeable variation in bank credit across locations and time (Prakash et al., 2019).

To pin down exogenous variations in credit supply, we use movements in the global price of gold. Gold is a highly popular asset among Indian households and banks and frequently used as collateral to obtain so-called gold loans (RBI, 2013). Therefore, a higher gold price increases the nominal value of the collateral and allows the gold-holding banks to extend higher credit lines in a way that is orthogonal to the state of the economy. Using district-level credit data from the Reserve Bank of India between 1998 and 2017, we show that a 10% increase in the gold price leads to a 1.5% increase in credit in the short-run and 4% higher lending in the medium run. We also estimate a dynamic response of GDP to the same shock: It expands over time with a structural elasticity with respect to credit supply between 0.1 and 0.2.

The informal sector is by nature poorly measured in national account statistics, either directly through firm surveys or indirectly exploiting discrepancies in official statistics.[2] We proxy human economy activity using night-time light emissions (Henderson et al., 2012). Following an expansion in credit supply, we estimate that economic activity measured in this way actually temporarily contracts and only grows within a matter of 3-5 years. This is robust to alternative measurement of activity from outer space and for different periods in time.

[1] The figures on the size of the informal economy in India are estimates based on Medina and Schneider (2018) covering the period 1991 to 2015. The ILO reports the informal employment share to be over 90% of the entire workforce (defined as being without any social insurance), and looking at the subset of non-agricultural workforce it is estimated at 85% Mehrotra et al. (2019). While a large part of informality is in farming, an important part in terms of employment is also among self-employed sellers and peddlers living close to the poverty line. The phenomenon is between the extremes of economic activities with no registration and compliance with regulations at all to firms that are well established with formally hired labour but hide some of their sales from authorities to avoid taxation (La Porta and Shleifer, 2014).

[2] We define the shadow/informal economy as all economic activities that are hidden from official authorities for monetary, regulatory, and institutional reasons (Medina and Schneider, 2018). An increasing tax and social contribution burden are among the main driving factors to avoid formalisation and to operate in the shadow (Schneider, 2005; Schneider et al., 2010). Our analysis abstracts from illegal or criminal activities and considers the shadow economy as economic and productive activities.

From these estimates, we can infer changes in informal activities through the inverse elasticity between formal activity and total, night-time measured activity. We find that the exogenous credit supply expansions leads to a stark re-allocation of production from the informal to the formal sector. The sharp decrease in informal activities is stronger than the expansion of formal output at least in the short run. We relate this to the re-allocation process itself: Productive capacities take time to be built in the formal sector and the economy only fully reaps the benefits of higher credit supply after a number of years.

We provide causal evidence on the structural elasticities of output to credit supply using the price of gold. Shocks from political and economic events outside an economy have been used to study credit supply in the context of a developing country before (Khwaja and Mian, 2008). It is well established that credit supply and access to finance have significant effects on real economic outcomes. Burgess and Pande (2005) use a policy implemented by the Reserve Bank of India that required commercial banks to open branches in rural areas whenever opening one in an area that is already banked. The regions that received access to banking services due to this policy saw lower levels of poverty and higher non-agricultural output as a consequence.

Financial intermediation in general and deepening in particular is found to contribute to economic growth, more so in the context of developing than industrial countries, whereas productivity growth is identified to be the strongest channel (e.g. Levine et al., 2000; Calderón and Liu, 2003). Similarly, it is found to impact informality negatively, Beck and Hoseini (2014) study the Indian manufacturing sector exploiting cross-industry variation in reliance on external financing, and disentangle two channels through which financial deepening reduces informality. On the one hand, addressing opportunistic informality by reducing the entry barrier to the formal sector, particularly for small firms, and on the other hand, increasing productivity of formal firms. They found no significant impact on the productivity of informal sector firms. The findings are in line with firm-level evidence from cross-country studies (e.g. La Porta and Shleifer, 2008; Bose et al., 2012; Beck et al., 2014).

Many of the existing empirical studies merely control for potential endogeneity of financial development and other determinants of the informal economy. Our paper addresses this concern by exploiting gold price variations, others exploited regulatory frameworks for exogenous variation in banking availability (Capasso and Jappelli, 2013) or use a panel VAR approach (Berdiev and Saunoris, 2016).

The paper relates to the discussion of financial frictions and the (mis-)allocation of resources across sectors and thus the variation in total factor productivity and living standards across countries (Hsieh and Klenow, 2009; Buera et al., 2011; Restuccia and Rogerson, 2017). If capital or labour have different marginal productivities in two sectors, financial constraints in one sector will have effects on aggregate total factor productivity.

We add to a growing literature by both macroeconomists and development economists using detailed geodata to study aggregate economic outcomes. With respect to India, Chodorow-Reich et al. (2020) find that the Indian government's attempt at demonetizing an illicit economy heavily based on cash lead to tarnished economic outcomes in districts where high-denomination banknotes had been abundant. Asher and Novosad (2017) find that after narrow local elections that end in favour of the ruling party, the respective locality receives more public funds and performs better both in terms of share prices of public firms, but also in terms of economic activity. Inspired by Henderson et al. (2012), the latter is measured by night-time light emissions captured by satellites in outer space. Applied to the context of India, Prakash et al. (2019) study the correlations between night-time lights, GDP and other macroeconomic indicators (e.g industrial production, credit growth) covering the years 1992 to 2017 and find a reasonably robust relationship suggesting that the night-time lights have a statistically significant predictive power for the Indian economic activity. In contrast to global estimates of the elasticity between night-time lights and state-level GDP the magnitude is smaller aligned with our finding. The authors report a coefficient for agricultural activity that is positive and higher than that of GDP, this in contrast to findings suggesting night-lights do not adequately capture changes in agricultural growth (e.g. Keola et al., 2015). They suggest the explanation that agricultural production is the major determinant of India's consumption demand as well as that harvesting seasons coincide with major Indian festivals when use of night-lights increases.

The remainder of the paper is organized as follows: Section 3.2 describes the different district- and state-level data sources and variables employed. Section 3.3 outlines and validates the empirical strategy to identify credit supply shocks using gold price changes. In Section 3.4 we estimate the dynamic responses of reported GDP and estimates total economic activity and derive the implied developments of the shadow economy as a residual before concluding in Section 3.5.

3.2 Data

This Section provides information and descriptives statistics on the two main datasets used in the paper, which we combine to an unbalanced panel of Indian districts at the annual frequency from 1998 to 2017. More details appear in the Appendix Section A.1.

3.2.1 District-level lending

Estimating the effect of financial deepening on the dynamics of total economic activity, distinguishing formal and informal sectors, requires detailed data on credit access and availability, both at a spatially and temporally fine-grained level. The RBI publishes end-of-quarter data on deposits and credits outstanding by district. The Quarterly Statistics on Deposits and Credit of Scheduled Commerical Banks are available since 1998-q4 and contain information at the district level on the number of reporting branches, deposits held in accounts opened at branches, and loans granted by loan officers at branches.[3] The branch-level reporting spatially confines the credit flows to within the boundaries of districts, in terms of supply and largely also in terms of demand. The disaggregated data allows to analyse the response of credit variables in combination with other hypothesis that follow from the theoretical literature underlying credit flows.

The scheduled commercial banks of India are divided into six categories, of which we include all except foreign banks resulting in 89 different banks over the sample period: 12 public sector, 22 private sector, 11 small finance, 2 payments, 42 regional rural banks.[4]

Our main explanatory variable for financial deepening is credit supply by commercial banks, as reported by end of the fiscal year per district.

3.2.2 Total economic activity: night light data from satellites

To measure the total economic activity we rely on a consistent measurement of light emissions from Earth during the sample period of 1998 to 2017 and in such a time resolution as to aggregate it over a fiscal year. Most of the literature employed one of the two series, the annual DMSP-OLS nighttime lights composites covering 1992 to 2013 or the monthly VIIRS-DNB nighttime covering 2012-April to present.[5] Limited work has been done to combine and inter-calibrate the two time series composites for a consistent coverage from 1992 to present.

[3] The numbers are reported in rupees Rs Crore. The time series is digitised and available online on the Database on Indian Economy (DBIE), Statement No.4A, starting 2003q4. The earlier series 1998q4 until 2003q2 are available under Statement No.9 from archived PDFs. We digitised these older series, accounting for names in Hindi, change of names over time, and formation of districts and states.

[4] The commercial scheduled banks SCBs in India are included in the Second Schedule of Reserve Bank of India Act, 1934, fulfilling the criteria in section 42(6)(a) of said Act. A scheduled bank is eligible for debts/loans at the RBI repo rate, and is a member of the clearing house. The list of SCBs can be found here.

[5] See e.g. Henderson et al. (2012) for the DMSP-OLS (Defense Meteorological Satellite Program - Operational Linescan System) and e.g. Chodorow-Reich et al. (2020) for the VIIRS-DNB (Visible Infrared Imaging Radiometer Suite - Day-Night Band) data.

The Light Every Night (LEN) data project publishes daily nighttime imagery from the DMSP-OLS and VIIRS-DNB sensors with data spanning from 1992 to 2017, and 2012 to 2020, respectively. The data are sourced from the NOAA National Centers for Environmental Information (NCEI) archive and made available as processed imagery bands.[6] The daily frequency allows us to aggregate the observations for each fiscal year to match the bank lending and borrowing. The LEN dataset has a continuous time series using the same sensor technology (DMSP-OLS) albeit with different satellites over the time span of the study.[7] We account for sensitivity checks using the newer sensor technology of the VIIRS-DNB for a subset of our dataset.

We intersect the daily satellite imagery, split into several tiles, with the administrative divisions of India's districts to calculate the mean of light measured in each pixel within the boundaries of a district per day. Due to computational limits we select images of five random days per month to aggregate daily means to monthly means and, to their fiscal yearly aggregation as sum or average.

As outlined above the DMSP-OLS sensor has a spatial resolution of ca. 4.9km at night, and the digital values of each pixel range from no light at 0, to full light at 63 (a low 6-bit quantization). Satellite imagery captures besides aspects of human economic activity like city lights, fishing boats, gas flares or agricultural fires, it also includes nighttime lights phenomena such as auroras, lightning or stray light, or more challenging cloud covers that obscure the visibility of lights emitted from Earth. We use the DMSP-OLS VIS where non-human light emissions are removed and non-light values are set to zero (processed using algorithms). Monthly means of several days of data account for a certain stable light emission and cloudy days of zero detectable lights.

The old generation sensor used for the dataset employed has its limitations: the low radiometric resolution (6-bit quantization) leads to saturation of light pixels in urban centres where the highest possible digital number is reached (i.e. 63), hence no further variation can be observed. This ceiling is of concern for the states that are dominated by urban settlement, e.g. the urban union territory Chandigarh, state NCT Delhi. There are several city-districts, e.g. Mumbai City, New Delhi, Kolkata, Hy-

[6] The project is led by the World Bank, NOAA, University of Michigan and was introduced in January 2021 in the following World Bank blog post. The data can be accessed via Amazon Web Services at AWS: Light Every Night. More details on sources in Appendix Section A.1.

[7] For the sample period of the study eight different DMSP satellites F12-F19 were launched, most with multiple overlap while in orbit. The imagery among the set of satellites is selected such as to have the high quality nighttime data. Following the recommendation of NOAA/World Bank we select: F14 (1998, 2003), F16 (2004-2008), F18 (2009-2010), F15 (2011-2017). The DMSP-OLS is an oscillating scan radiometer with 2 spectral bands, of which we use the Visible Near Infrared VNIR (short VIS) that has low-light imaging capabilities. The satellites complete 14 orbits a day, generating global daytime and nighttime coverage of the earth every 24 hours.

derabad, Chennai, Chandigarh. We account for ceiling effects by excluding the urban dominated districts in a sensitivity analysis.

3.2.3 Other variables

The dataset is constructed at two different levels of administrative division, the state and district level. Of the current 28 states and 8 Union territories we include all 36. We identify 758 different districts over time, of currently 742 districts. Figure C1 illustrates the boundaries as of 2017. The measurement of the formal economy is crucial as the difference to total economic activity observed on the basis of nighttime low-light emissions observed from outer space constitutes our measurement of the informal economy.

As we will describe below, the price of precious metals will provide the source of exogenous variation we use for identification. We therefore extract a time series of the gold (and silver) prices in US dollar per Troy ounce (London afternoon fixing). For all variables, we construct growth rates as log differences of the last observation available in a fiscal year, which in India lasts from April 1 to March 31. All nominal variables, including the gold price, are deflated by the value of the consumer price index at the end of each fiscal year. Furthermore, we collect growth rates of real GDP of Indian states as a measure of formal output from different vintages published by the national statistical office ("Gross State Domestic Product at constant prices"). The state level is the finest level of disaggregation for which we could access data on formal output. Therefore, we use the district panel wherever possible but state-level whenever needed (whereas we sum all variables over districts within a state). The 2011 Census is used for all information regarding demographic characteristics, e.g. the distribution of religions within geographies.

This is the first study that employs district-level bank lending data over a time span of 19 years, combined with recent time series data on nightlights.

3.2.4 Summary statistics

Table 3.1 reports cross-state and cross-district summary statistics over the entire sample period. The median district experiences a log difference in credit supply of 15.9, while the nighttime light emissions change by 0.855 log difference. The comparable cross-state statistics are at 15.7 and 1.177, respectively. The VIIRS nightlight figures are comparable to the LEN ones across state and district levels.

Panel C in Table 3.1 describes socio-economic variable reflecting several aspects of the economic measurement studied. The district on average covers an area of 4964 $km2$

with large standard deviations across the sample. Regarding the dominant land cover, 5% of district and 9% of state area respectively are describe to be urban, in contrast to a much larger share being classified as treecover, at 25% for districts and 33% at the state level. A state contains on average two locations of historical Mughal mints.

Table 3.1: Descriptive statistics at the state and district level

Variable name	State level				District level			
	Sample mean	Std. dev.	Median	N	Sample mean	Std. dev.	Median	N
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Panel A: Financial market variables								
Credit	155180	930367	4745	657	54573	409986.3	6948	12264
Ln-gr credit	15	22	16	626	16	16.3	16	11592
Deposit	191320	1059458	11080	657	74231	421025.9	15488	12264
Ln-gr deposit	13	19	14	626	14	15.4	14	11592
Number of offices	169	412	80	657	146	188.3	101	12264
Panel B: Nightlight variables								
LEN Nightlight (mean)	12	8	10	657	10	5.4	9	12244
LEN Nightlight (log-gr mean)	3	16	1	657	3	19.2	1	12244
LEN Nightlight (sum)	47	33	38	657	39	21	34	12244
LEN Nightlight (log-gr sum)	1	9	1	657	1	11.1	0	12244
VIIRS Nightlight (mean)	10	2	10	168	10	2	10	3292
VIIRS Nightlight (gr mean)	3	12	3	168	3	12.2	2	3292
Panel C: Socio-economic variables								
Area km2	96079	101624	55604	657	4964	4598.2	3788	12264
Population density 2000	938	1635	353	657	639	2401.6	316	12264
Population density 2015	1201	2151	460	657	777	2412	396	12264
Muslim-share 2011	0	0	0	654	0	0.2	0	12213
Share urban 2015	9	14	4	657	5	8.5	3	12264
Share treecover 2015	33	24	24	657	25	23.6	15	12264
Elevation (m)	586	708	289	657	475	700	251	12264
Presence capital city	1	0	1	657	0	0.2	0	12264
Number Mughal mints	2	3	1	657	0	0.3	0	12264

Notes: Summary statistics of the outcome and explanatory variables by district- and state-level.

3.2.5 The elasticity of nightlight emissions and GDP

First, we verify the validity of nightlight emissions as a measure of total economic activity. As Henderson et al. (2012), we rely on the fact that output production uses electricity, the use of which can be captured from outer space during nighttime. We create an index of light emissions for each district and state, taking the average across pixels within the respective borders. The first test then regresses the growth rate of real state-wide GDP, which is published by the statistical office and denoted $y^f_{s,t} - y^f_{s,t-1}$ for formal output, on the growth rate of nightlight emissions.

$$y^f_{s,t} - y^f_{s,t-1} = \eta \left(nl_{s,t} - nl_{s,t-1}\right) \tag{3.1}$$

Lower-case letters denote log indices. Table 3.2 shows that the estimate of the respective elasticity η is low but positive and highly statistically significant. Quantitatively, the elasticity is 0.03 and relatively precisely estimated, such that a 10% increase in nightlight intensity can be associated with 0.3% higher GDP. Furthermore, it is robust in two dimensions: First, we construct the index as a sum of pixels within a state, such that higher states have higher output. The second alteration, shown in columns (3) and (4), is that we transform the real GDP growth rates to a log index and regress the index on the log night light index directly, absorbing level differences with a state fixed effect. The respective estimates are very similar, even though the standard errors now render inference more difficult.

Table 3.2: GDP and night lights

	$y^f_{s,t} - y^f_{s,t-1}$		$y^f_{s,t}$	
	Mean intensity (1)	Sum (2)	Mean (3)	Sum (4)
$nl_{s,t} - nl_{s,t-1}$	0.031***	0.029***		
	(0.004)	(0.005)		
$nl_{s,t}$			0.026	0.026
			(0.031)	(0.031)
State fixed effect	No	No	Yes	Yes
Observations	585	585	583	583
States	31	31	31	31

Notes: Columns (1) and (2) show regression outputs of the growth rate of statewide GDP and night light emissions. (3) and (4) do the same in log levels, including a constant for each state. (1) and (3) take the mean intensity of pixels in a state, (2) and (4) the sum. Standard errors are clustered by state. Sample: 1999-2016. Significance levels: *** 1% ** 5%, * 10%.

Ultimately, we want to create a measure of total economic activity at the district level that captures both the formal sector, as (imprecisely) measured by state GDP, and the informal sector. Based on the above elasticity estimation, this measure is defined as

$$y^t_{d,t} - y^t_{d,t-1} \equiv \hat{\eta} \times (nl_{d,t} - nl_{d,t-1}) \tag{3.2}$$

i.e. we use the growth rate of nightlight emissions to get a projection of output growth. Implicitly, this assumes that the formal and informal sectors have the same elasticity with respect to output, an assumption which we will further discuss below.

3.3 Credit supply across districts in India

We estimate panel local projections on the merged dataset of bank credit and economy activity. Because credit and economic activity, whether formal or informal, can be endogenously intertwined in a multitude of ways, we first outline and validate our empirical strategy to the identification of credit supply shocks.

3.3.1 Empirical strategy

Our empirical strategy relies on the extraordinary role gold carries in the Indian society and economy as a store of value and its implications for the regulatory framework of the Indian banking market. Gold is deeply rooted in Indian culture as a safe asset, as a status symbol and an integral part of gift-giving and ceremonies across many religions. While barely producing gold itself, India is one of the countries with the highest demand for gold (on roughly equal footing with China). Kannan and Dhal (2008) discuss the role of gold as a savings device and find significant demand elasticities with respect to wealth and the price. Rather than looking at demand for gold at a given point in time, we exploit price fluctuations and thus valuation effects of the stock of gold already in the country. Gold loans are a common credit product in India, allowing borrowers to access liquid funds while simultaneously physically hold the metal (as jewellery or bullion). The process of obtaining cash when pawning gold is relatively informal, which is why it is especially popular in rural communities (RBI, 2013). The Reserve Bank of India requires the loan-to-value ratio for gold loans to be no higher than 75%.[8] With gold acting as a common collateral asset, an increase of its price expands the credit constraint of Indian households and businesses, allowing to bridge temporary cash crunches in particular because gold loans are bullet loans, thus the principal is paid at the end of the term, rather than in smaller instalments.

A regulatory requirement by the RBI requires commercial banks to hold gold, too. The Statutory Liquidity Ratio (SLR) regulates that banks must hold a minimum fraction of deposits in liquid assets (on their balance sheet, rather than with deposits at the RBI). Beyond cash and a small group of RBI-approved securities,[9] gold counts toward satisfying the SLR. The SLR is one of RBI's main policy tools and could be as high as 40%, although it was below 25% since the late 1990s and has been on a general downward path since the Great Recession. In each circular, the RBI announces a path for the SLR for the future and usually specifies the assets compatible with the definition of liquid assets. For scheduled commercial banks, gold is usually mentioned in second place.[10] Nevertheless, Indian banks have significant gold holdings. Increasing gold prices therefore increase the nominal value of bank reserves and thus expand the regulatory lending capacity.

Gold does not directly affect GDP by expanding the productive capacity of the econ-

[8] The LTV threshold was temporarily increased to 0.9 in 2020, a period which is not part of our data sample.

[9] This includes for example Treasury Bills and State Development Loans. The SLR is regulated by Sections 24 and 56 of the Banking Regulation Act of 1949.

[10] See the RBI circular of December 10, 2015 for an example.

omy. However, due to its prominent role as a consumer of gold, developments in India might be able to affect the gold price, rendering identification of a credit supply shock through the global gold price difficult. In Appendix B, we show that positive stock market news in India are indeed positively correlated with the gold price, contrary to for example stock markets in the U.S. Nevertheless, the estimated coefficient is too small and the explanatory power far too low for the gold price to be meaningfully impacted by economic conditions in India.

3.3.2 The gold price and credit supply

We first show that fluctuations in the gold price indeed act as a shifter of credit supply in India. To that end, we estimate the following local projections.

$$c_{d,t+h} - c_{d,t-1} = \beta^h \Delta \text{Gold}_t + \gamma^h X_t + \delta_d + u_{d,t+h} \tag{3.3}$$

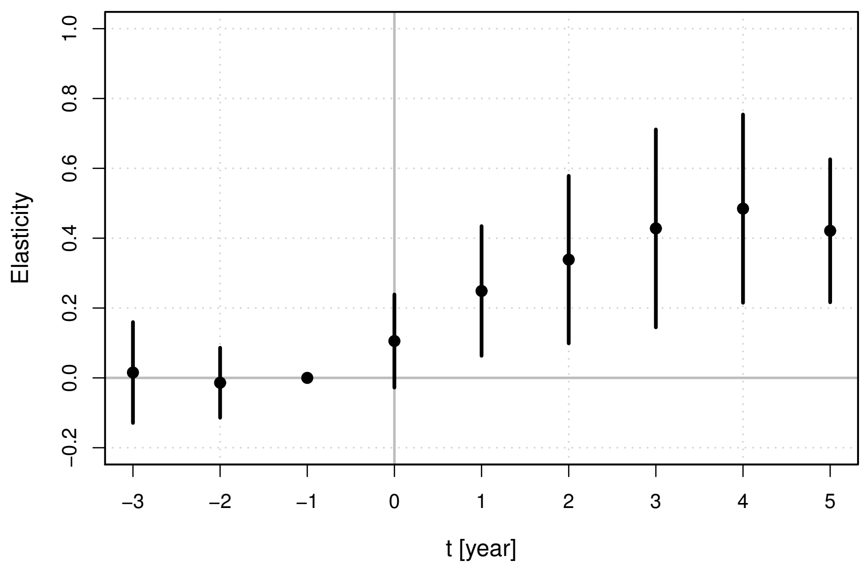
where the left-hand side variable is the log difference of district-level credit between the end of fiscal year $t-1$ and a horizon $t+h$, $h = \{-3, ..., 5\}$. The main explanatory variable is the log difference of the gold price for the respective period. Because it has no variation in the cross-section, we include time-specific global control variables in the vector X, namely the following macro variables: the first lag of ΔGold_t, the growth rates of GDP in the US, the European Union and China, as well as bilateral nominal exchange rate changes of the Indian rupee with respect to the former two markets. The idea is to purge signals in the gold price from developments in international markets that might affect the Indian economy via external demand. We further control for contemporaneous changes in the statutory liquidity ratio and the repo rate of the Reserve Bank. δ_d is a district fixed effect.

Following Jordà (2005), an impulse response to a 1% increase in the gold price can be constructed by stacking the estimates $\hat{\beta}^h$ across all horizons.[11] They are illustrated in Figure 3.1 and summarized in Table D1.

According to these estimates, a percentage point increase in the gold price increases bank credit already contemporaneously with an elasticity of 0.11. The peak effect is

[11] Jordà (2005) first proposed estimating impulse responses by directly regressing outcome variables for each of the h periods in the future on covariates in period t, rather than estimating a recursive system and extrapolating impulse responses from a typically low number of autocovariances (as we do in Appendix B with aggregate time series). The biggest advantage of the methodology for our context is that it is flexibly applicable to panel data with fixed effects and potentially non-linear interactions. Additionally, Li et al. (2021) show that local projections have the property of lower bias at longer-run horizons, even though at the expense of estimation efficiency. Local projections do not solve the identification problem, but since we aim to identify the credit supply shock with the price of gold as an instrument, dynamic first-stage results are obtained by directly regressing credit growth between $t-1$ and $t+h$ on the shock in t.

Figure 3.1: Gold price shocks and credit supply



Notes: Local projections of credit outstanding by district and fiscal year on changes of the gold price in the respective time period (Equation 3.3). Control variables: lagged gold price change, contemporaneous change in SLR and repo rates and global control variables (US, EU and Chinese GDP growth and exchange rate fluctuations of the INR with respect to USD and EU). 95% confidence bands based on standard errors clustered by fiscal year and district. Sample: 1999-2017.

reached after 2-4 years, when credit has increased by 0.4%. These effects are not only significant but also economically meaningful. If all gold was used as collateral with a loan-to-value requirement of 0.75, loans could increase as much as 0.75% directly, and potentially more due to amplification via an expansion of the real economy (Kiyotaki and Moore, 1997). In Figure 3.1, we also plot estimates for credit in years prior to the change in gold prices, again relative to $c_{d,t-1}$. There is no evidence of an economically or statistically significant pre-trend.

We provide a number of additional specifications to stress the robustness of this result. First, we regress the gold price change over a year on the growth rate of Indian GDP in the current and past year. We then redefine the residual of that regression as the gold price shock, i.e. we purge information in the gold price that is potentially driven by developments in India. Despite India being one of the world's largest consumers of gold, there is little evidence that its demand explains a meaningful fraction of the gold price. For example, the coefficients in the above regression are far from statistically significant, with an R^2 of 0.02. In Appendix B we confirm this using higher-frequency stock prices. The first panel of Table 3.3 shows the local projection coefficients for the residualized gold price shock, denoted $\Delta\widetilde{G1}$. They are in line with the baseline estimates. Furthermore, we provide evidence on meaningfulness of the gold price for credit supply in India by means of 3-variable vector autoregression with aggregate time series. The three variables are GDP, bank lending and the bank lending rate. In a Proxy-SVAR (see e.g. Gertler and Karadi, 2015), we instrument the reduced-form residuals of bank lending with gold price shocks, allowing to identify the responses of all variables in the system. The gold price carries enough statistical power to explain deviations of credit from the historical (auto-)correlations. An advantage of this approach is that it allows us to include a series of the price of credit, which is information we cannot observe in the panel data of the RBI. Crucially, the gold price shock drives the quantity and price of bank lending in opposite directions, as is to be expected by a shift in credit supply. The remaining robustness tests are performed based on the bank credit panel data and are summarized in Table 3.3.

Silver Most importantly, we verify the special role of gold in India's regulatory environment and thus as an instrument for credit supply shocks by showing that changes in the price of another popular commodity do not have the same easing effect on lending capacities. In the second panel of Table 3.3 we run our baseline regression 3.3 but replace the current and lagged gold price changes with those of silver. India is responsible for 30% of physical investment in silver globally.[12] While bank lending against silver collateral exists, it is less common than with gold and, importantly, it does not account toward bank's compliance with the regulatory reserve requirements. The estimated effects are positive, but much smaller than the gold equivalents. The much weaker relationship between silver price movements as a "placebo" and Indian credit cycles is evidence of the special nature of gold in financial intermediation in India.

Share of Muslims For the third validation, we use the fact that gold loans are much less common among India's Muslim communities. We could in principle interact the gold price change with the share of the Muslim population in a given district. This is available in the Census of India for the year 2011. To circumvent endogeneity concerns of the Muslim population's mobility patterns in response to credit supply prior to 2011, we instrument the Census-based share using historical Mughal mints. Jha (2013) shows that the location of gold and silver mints established under Mughal emperors in the 16th century are indicative of where today's Muslim communities in India still cluster.[13] Figure 3.2 overlaps the mints and the 2011 Muslim shares per district. The first stage regression indicates that an additional historical mint increases the Muslim share by 7 percentage point and that the estimate is significant at the 5%

[12] Source: World Silver Survey 2020

[13] The median state has a share of the Muslim population of around 8%. Seven states have a share of 15% or higher, while two states (Lakshadweep as well as Jammu and Kashmir) have a majority Muslim population. The state of Telangana did not exist in 2011 and is thus omitted from the second panel of Table 3.3.

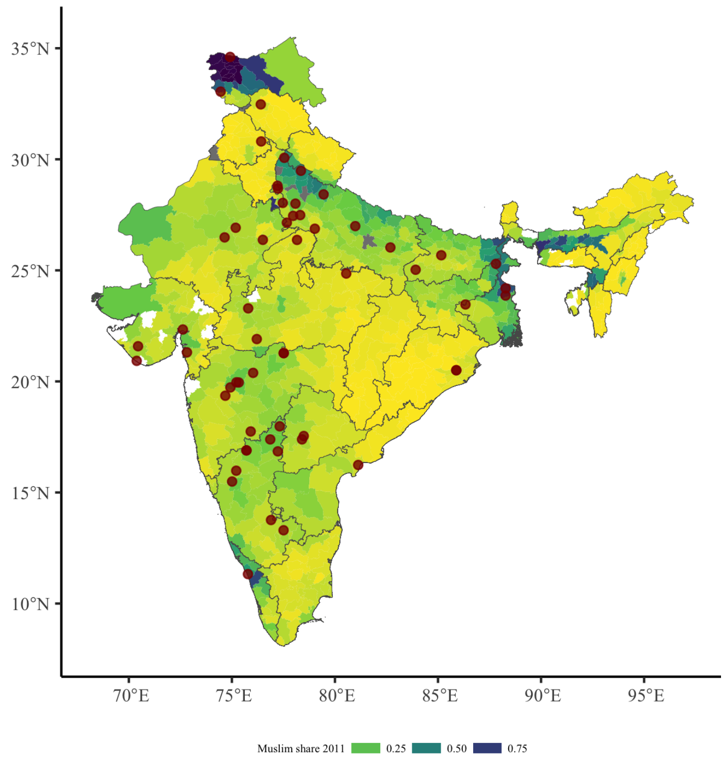
Table 3.3: Robustness

	$c_{d,t+h} - c_{d,t-1}$				
Gold, residualized I	$h=0$	$h=1$	$h=2$	$h=3$	$h=4$
$\Delta\widetilde{G1}_t$	0.095	0.270***	0.450***	0.535***	0.596***
	(0.073)	(0.103)	(0.168)	(0.169)	(0.180)
Observations	11557	10860	10171	9511	8854
Districts	697	689	660	657	652
R^2	0.15	0.29	0.39	0.30	0.31
Silver placebo:	$h=0$	$h=1$	$h=2$	$h=3$	$h=4$
ΔSilver_t	0.038	0.086***	0.106*	0.114	0.158***
	(0.028)	(0.033)	(0.056)	(0.073)	(0.054)
Observations	11557	10860	10171	9511	8854
Districts	697	689	660	657	652
R^2	0.15	0.29	0.38	0.28	0.30
Share of Muslim population:	$h=0$	$h=1$	$h=2$	$h=3$	$h=4$
ΔGold_t	0.158**	0.334***	0.451***	0.539***	0.573***
	(0.070)	(0.103)	(0.145)	(0.178)	(0.186)
$\Delta\text{Gold}_t \times \text{Mughal mints}_d$	-0.025**	-0.043**	-0.060***	-0.056**	-0.054**
	(0.012)	(0.018)	(0.022)	(0.024)	(0.025)
Observations	11536	10849	10170	9511	8854
Districts	687	679	659	657	652
R^2	0.16	0.29	0.39	0.30	0.31
No controls:	$h=0$	$h=1$	$h=2$	$h=3$	$h=4$
ΔGold_t	0.121**	0.211**	0.332***	0.411**	0.412**
	(0.052)	(0.089)	(0.121)	(0.161)	(0.198)
Observations	11557	10860	10171	9511	8854
Districts	697	689	660	657	652
R^2	0.11	0.20	0.29	0.20	0.17
Balanced panel:	$h=0$	$h=1$	$h=2$	$h=3$	$h=4$
ΔGold_t	0.137**	0.246**	0.302*	0.331*	0.469***
	(0.063)	(0.099)	(0.164)	(0.179)	(0.154)
Observations	8854	8854	8854	8854	8854
Districts	652	652	652	652	652
R^2	0.07	0.17	0.21	0.24	0.30

Notes: Local projection of credit outstanding by district and fiscal year on changes of the gold price in the respective time period. The following changes are made with respect to the baseline regression 3.3: The upper-most panel replaces the gold price with residuals from a regression of the gold price changes on current and lagged GDP growth rates. The second one replaces all gold price changes with the price of silver. The third panel interacts the gold price with the number of historical Mughal mints, which are themselves a proxy for the share of the Muslim population in the district according to the 2011 Census. The fourth panel omits all control variables, including the lagged gold price, and the final conditions on districts that are observed in all periods between t-1 and t+4. Standard errors are clustered by fiscal year and district. Sample: 1999-2017 (last panel: 1999-2013). Significance levels: *** 1% ** 5%, * 10%.

level with an F-statistics of 14.4. We then augment our baseline local projections for

Figure 3.2: First stage of Muslim share 2011 on 16th century Mughal mints location at the district level



Notes: The figure illustrates the first stage between the instrument of the location of Mughal Mints plotted as red dots and the Muslim share as reported in the Census 2011 at district level, where darker greens indicate higher Muslim shares. Furthermore, the map demarcates the state boundaries of the 28 States an 6 Union Territories as of 2017. The first stage regression of Muslim share on number of historical Mughal Mints intersecting with the district controlling for state fixed effects allowing for a heteroskedastic error term shows a strong relationship of 0.07 significant at the 5% level. The corresponding F-statistic is: 14.4. Mughal mints locations are based on Jha (2013).

local credit with the interaction of the gold price and the number of historical Mughal mints. The baseline effect becomes slightly stronger and the interaction coefficient is strongly negative and significant. The estimates imply that credit supply in a district with a high density of historical mints (and consequently a larger share of Muslims today) is much less affected by gold price movements.

The fourth panel of Table 3.3 shows that our results are not driven by the choice of control variables. When we omit all time-specific macro control variables, the estimated coefficients are very similar and significantly positive at the 5% significance level. Finally, we condition on the subsample of districts that we observe for all periods between one period prior to and four periods after the change in the gold price.[14]

[14] There are two reasons for the unbalancedness of the baseline panel: First, there is re-districting, which we try to address as much as possible (see Section 3.2.1). Second, local projections of the fourth lead of a variable will automatically exclude the last four time periods due to the time truncation of the

Again the estimated elasticities are very similar.

Ex ante financial situation Exploiting the cross-sectional dimension of our data, we additionally interact the change in the gold price ΔGold_t with a district-level estimate of financial leverage, defined as the amount of credit outstanding relative to deposits $\left(\frac{\text{Credit}_{d,t-1}}{\text{Deposits}_{d,t-1}}\right)$. For each year, we standardize this measure by dividing a district's credit-to-deposit ratio by the average across districts and dividing by the standard deviation. Table 3.4 shows the results. While the baseline effect of the gold price is almost unaffected, it becomes clear that districts that had an ex ante higher ratio of bank credit to bank deposits have an amplified expansion of credit supply following the shock. The magnitude is about 0.06 to 0.15% for every standard deviation in leverage. We interpret these findings through the lens of two standard financial frictions, namely the balance-sheet channel (Kiyotaki and Moore, 1997; Bernanke et al., 1999) and the channel of bank lending (Bernanke and Blinder, 1988), arguing that the former affects Indian districts much more uniformly. If a bank's branch that operates only in district *a* has exhausted its lending capacity given reserve requirements, i.e. has a relatively high ratio of credit to deposits, an increase in the gold price will allow it to lend the now excess reserves to the district, where credit supply increases as a consequence. In turn, the bank in district *b* has a low leverage ratio and a non-binding reserve constraint, which is why it is relatively less affected by changes in the gold price. On the other hand, the financial accelerator framework states that households and firms can obtain credit by posting collateral, including gold. If the price of the collateral increases, the borrowing capacity expands and frees up liquidity for investment, but it does so regardless of whether the borrower lives in district *a* or *b* (as long as there is a lender in the district).

Our results show that both effects are at work: While credit increases across all districts after the gold price has gone up, it does so more in districts with high credit relative to deposit funding. In the last panel, we show that the same is true at the state level. One might argue that bank balance sheet effects are more relevant at the state than at the district level, because local banks might channel funds across district lines but less across state lines. We find, first, that our baseline effect is significant and at least as strong in magnitude as the district-level regression. Second, the interaction with the standardized lagged credit-to-deposit ratio is estimated to be positive, although statistical power weakens with a sample of only 36 localities.

Both the balance sheet and bank lending channel can be asymmetric in the sense that

data. Since the 2016 de-monetization episode plays a prominent role in local credit market outcomes and the shadow economy in India (Chodorow-Reich et al., 2020), we include those time periods in the baseline regression.

Table 3.4: Heterogeneity in bank credit supply effects

	$c_{d,t+h} - c_{d,t-1}$				
Leverage:	$h=0$	$h=1$	$h=2$	$h=3$	$h=4$
ΔGold_t	0.111	0.255***	0.341***	0.439***	0.475***
	(0.069)	(0.096)	(0.126)	(0.153)	(0.157)
$\Delta\text{Gold}_t \times \frac{\text{Credit}_{d,t-1}}{\text{Deposits}_{d,t-1}}$	0.015	0.056**	0.108***	0.148***	0.140***
	(0.018)	(0.028)	(0.034)	(0.034)	(0.038)
Observations	11557	10860	10171	9511	8854
Districts	697	689	660	657	652
R^2	0.18	0.35	0.48	0.43	0.46
In financial distress:	$h=0$	$h=1$	$h=2$	$h=3$	$h=4$
ΔGold_t	0.995***	0.601***	0.755***	0.726***	0.886***
	(0.019)	(0.026)	(0.031)	(0.039)	(0.043)
$\Delta\text{Gold}_t \times \frac{\text{Credit}_{d,t-1}}{\text{Deposits}_{d,t-1}}$	0.029	0.110*	0.211***	0.299***	0.318***
	(0.034)	(0.064)	(0.072)	(0.063)	(0.048)
Observations	3162	2507	2497	2496	1850
Districts	666	657	657	657	645
R^2	0.31	0.59	0.533	0.58	0.42
In financial distress excl. GFC:	$h=0$	$h=1$	$h=2$	$h=3$	$h=4$
ΔGold_t	0.248***	0.489***	0.640***	0.656***	0.782***
	(0.015)	(0.024)	(0.029)	(0.035)	(0.045)
$\Delta\text{Gold}_t \times \frac{\text{Credit}_{d,t-1}}{\text{Deposits}_{d,t-1}}$	0.039	0.102	0.183***	0.263***	0.291***
	(0.038)	(0.066)	(0.069)	(0.047)	(0.052)
Observations	2538	1883	1873	1872	1226
Districts	666	657	657	657	645
R^2	0.33	0.62	0.59	0.62	0.26
	$c_{s(d),t+h} - c_{s(d),t-1}$				
Leverage by state:	$h=0$	$h=1$	$h=2$	$h=3$	$h=4$
ΔGold_t	0.158*	0.284**	0.445**	0.519**	0.584**
	(0.083)	(0.112)	(0.173)	(0.215)	(0.247)
$\Delta\text{Gold}_t \times \frac{\text{Credit}_{s(d),t-1}}{\text{Deposits}_{s(d),t-1}}$	-0.005	0.028	0.095	0.114**	0.114**
	(0.048)	(0.051)	(0.067)	(0.056)	(0.052)
Observations	663	627	591	556	521
States	36	36	35	35	35
R^2	0.10	0.23	0.31	0.33	0.37

Notes: Local projection of credit outstanding by district and fiscal year on changes of the gold price in the respective time period. We augment regression 3.3 with an additional interaction of the ratio of loan to deposit in a district, which we standardize for each year. The average standard deviation across the sample period is 0.29. The middle panels conditions the sample on an augmented level of the financial stress index in the Indian banking sector (Senapati and Kavediya, 2020). The fourth first aggregates credit and deposits per fiscal year across districts in a state. Standard errors are clustered by fiscal year and district. Sample: 1999-2017 (middle panels: fiscal years 2004/05, (2008/09,) 2011/12, 2013/14, 2016/17). Significance levels: *** 1% ** 5%, * 10%.

they are amplified in times of tight credit constraints, or high financial stress (see e.g. Guerrieri and Iacoviello, 2017). We test this prediction in our data, splitting the sample into fiscal years with particularly high financial stress. Senapati and Kavediya (2020) develop an indicator of realized volatilities of Indian banking stocks. Five spikes can be identified which roughly coincide with the fiscal year frequency used in our data: the summer of 2004 (fiscal year 2004/05), the global financial crisis (2008/09), the fall of 2011 (fiscal year 2011/12), the taper tantrum episode (fiscal year 2013/14) as well as the winter of 2016/17. The second panel of Table 3.4 conditions the sample on these five time periods only. The estimated coefficients both for the direct as well as the interacted gold effect are at least double in size for the first three years. Thus an increase in the collateral value of gold during these times had a more expansionary effect on credit supply. Notice that the standard errors decrease despite a sample size of less than a third of the original data. To show that the effect is not driven by the global financial crisis, we exclude the fiscal year 2008/09 in the third panel. This reduces mostly the direct effects of the value of gold, especially in the short run, but all values are still significantly higher than in the full sample. Thus we conclude that there is a significant cyclical component in the way price movements of gold allow for credit supply expansions.

3.4 Real effects on formal and informal output

3.4.1 GDP growth

We examine how these extensions in credit supply lead to changes in the size of the economy. To that end, we regress changes of log real output y over h fiscal years on changes in log real credit over the respective period of time and the same vector of controls as in Regression 3.3. In particular, we estimate

$$y^i_{d,t+h} - y^i_{d,t-1} = \beta^h(c_{d,t+h} - c_{d,t-1}) + \gamma^h X_t + \delta_d + u_{d,t+h} \tag{3.4}$$

where $i = \{f, t\}$ denotes whether we use a measure of formal or total output including informal activities. The left-hand side variable is the cumulative growth rate of the respective index, and because we only observe period-by-period growth rates in practice, defined as $\sum_{k=0}^{h} y^i_{d,t+k} - y^i_{d,t+k-1}$. Notice that despite noisy data, we do not rely on winsorizing or disregarding large values.

Importantly, we instrument $(c_{d,t+h} - c_{d,t-1})$ based on our results from Section 3.3 with the contemporaneous change in the gold price, additionally interacted with the number of historical Mughal mints and the previous period's credit/deposit ratio. Our main measure of formal activity is GDP, which is not available by district, so all the above variables are measured at the state level, of which the full data covers 32 of them.[15] The structural elasticity between credit and output growth is between 0.1 and 0.2, as is shown in Table 3.5. A 10% gold price increase[16] expands credit supply by 4% thus generates direct and indirect effects on demand and supply between 0.4 and 0.8%. The magnitude of this estimate matches both the conditional co-movement of credit and demand for a large panel of countries in Cesa-Bianchi et al. (2018) as well as the impulse responses based on aggregate data in Appendix B.

Table 3.5: Baseline IV local projection estimates

	$y^f_{s,t+h} - y^f_{s,t-1}$				
	$h=0$	$h=1$	$h=2$	$h=3$	$h=4$
$c_{s,t+h} - c_{s,t-1}$	0.205**	0.178***	0.126***	0.096*	0.169***
	(0.088)	(0.047)	(0.031)	(0.054)	(0.050)
Observations	570	538	506	474	442
States	32	32	32	32	32
First-stage F-stat.	6.98	25.40	174.38	88.54	33.21
	$y^t_{d,t+h} - y^t_{d,t-1}$				
	$h=0$	$h=1$	$h=2$	$h=3$	$h=4$
$c_{d,t+h} - c_{d,t-1}$	-0.435	-0.288***	-0.175***	-0.072**	0.006
	(0.324)	(0.088)	(0.054)	(0.029)	(0.025)
Observations	11464	10836	10188	9551	8909
Districts	653	653	647	645	640
First-stage F-stat.	1.95	2.50	7.31	9.55	8.56

Notes: Local projections of log GDP differences (upper panel) and scaled total economic activity (lower panel) by state and fiscal year on changes of credit instrumented with the following variables: $\Delta\text{Gold}_t, \Delta\text{Gold}_t \times \text{Mughal mints}_s, \Delta\text{Gold}_t \times \frac{\text{Credit}_{s,t-1}}{\text{Deposits}_{s,t-1}}$. Control variables: lagged gold price change, contemporaneous change in SLR and repo rates and global control variables. Standard errors are clustered by fiscal year. Sample: 1999-2016. Significance levels: *** 1% ** 5%, * 10%.

3.4.2 Total economic activity

The main purpose of our estimations is to assess the effect of a credit supply expansion on the informal part of the economy. First, we estimate the effect on total economic activity (as estimated in Section 3.2.5), which we estimate at the district level with a sample size of over 10.000 observations. Apart from the unit of observation, the IV setting of the regression is identical. The structural estimate for the year of the

[15] The statistical office publishes state-level GDP growth rates, which we transform to an index of real GDP and take logs. The fiscal year 2016-17 is not consistently available and we omit it for all states.

[16] equivalent to two standard deviations of monthly gold price changes between 1998 and 2017.

gold price change itself is very imprecisely estimated. For the subsequent three years, however, a clear picture emerges: The estimated elasticities for a credit supply expansion on total economic activity are negative and largest in the beginning, even though formally measured GDP increases. The effect is fading out over time, with point estimates decreasing in absolute size with every year until becoming insignificant four years after the shock. If formal output increases and total economic activity decreases, it is already clear that the shadow economy must contract, but we can make this argument more formally by deconstructing the growth rate of total economic activity into its contributions from the formal and informal sector. Denote as y_t^s the output of the shadow economy and as $\phi^s \equiv y_t^s / y_t^t$ the share of the shadow economy. Then we can decompose:

$$
\begin{aligned}
y^t_{d,t+h} - y^t_{d,t-1} &= \phi^s (y^s_{d,t+h} - y^s_{d,t-1}) + (1-\phi^s)(y^f_{d,t+h} - y^f_{d,t-1}) \\
(y^s_{d,t+h} - y^s_{d,t-1}) &= \frac{1}{\phi^s}(y^t_{d,t+h} - y^t_{d,t-1}) - \frac{1-\phi^s}{\phi^s}(y^f_{d,t+h} - y^f_{d,t-1})
\end{aligned}
\tag{3.5}
$$

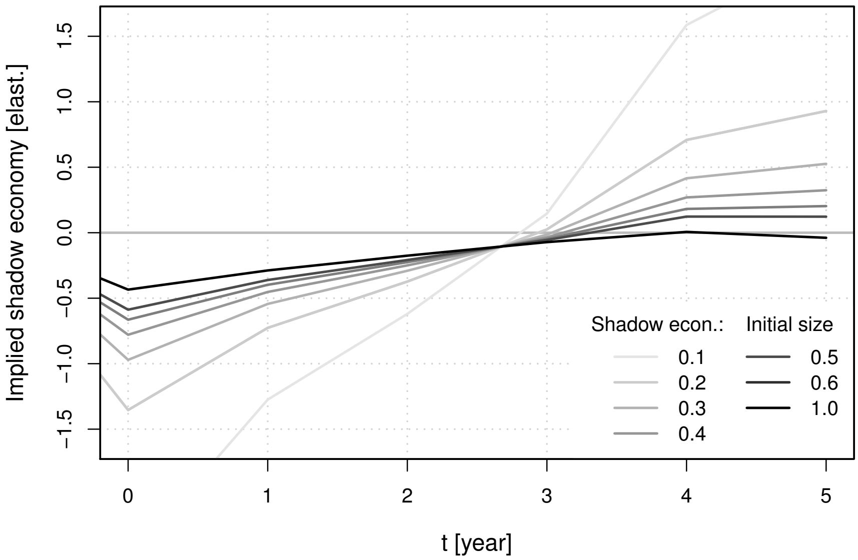
Since we observe both components in the right-hand side of Equation 3.5, we can generate an estimate of the reaction of the shadow economy conditional on the pre-existing size of the shadow economy. Figure 3.3 illustrates this path for different assumptions of ϕ^s. Estimates for the share of the economy typically lie between 10 and 40 percent. For this entire range, the initial contraction of the informal sector is large, namely between -0.3 to as much as -1.5% for every percent extension of credit. Therefore, we can conclude that the exogenous credit supply expansion leads to a reallocation of production from the informal to the formal sector. In order to obtain the more widely available bank credit, willing borrowers decide to formalize and devote resources elsewhere. The reallocation is strong enough to lead to a temporary contraction of total output.

We have two hypotheses for this phenomenon: First, producing in the formal sector tends to be more productive, because it allows the creditworthy, formalized firm to access production technologies it otherwise would not have. We address this issue in the next subsection. The second is that this reallocation is costly, and that investment in new production facilities only pays off over time. In the long run, however, both formal and informal activities will have expanded for all realistic values of initial ϕ^s.

3.4.3 Robustness and extensions

Nightlight elasticity in the shadow economy One caveat of our measure of total economic activity is that it implicitly assumes that one unit of production in the for-

Figure 3.3: Credit supply shocks and the shadow economy: Structural elasticities by initial ϕ^S



Notes: Elasticity of the shadow economy with respect to credit supply expansion implied by estimated of GDP and total economic activity (Equations 3.4 and 3.5). Sample: 1999-2017.

mal sector generates the same amount of nightlight emissions than a unit produced by an informal firm. It is known, however, that value added per worker in informal firms is substantially lower (La Porta and Shleifer, 2008; Ulyssea, 2018). La Porta and Shleifer (2014) show survey evidence that the ratio of value added per worker in informal firms is $\chi = 0.18$ that of formal ones (0.21 for small firms). This would bias our estimates because the lower degrees of nightlight emissions we find in the data does not imply the same reductions in informal output as it would if all production had the same elasticity with nightlight emissions. However, this ratio must not automatically translate to the same factor in nightlight emissions, because informal firms might use technology that emit less light than formal ones. Additionally, informal businesses might be more apt to operate during night hours, which would contribute to a tighter link between their production and our measurement of it. Nevertheless, we construct a direct measure of output in the shadow economy that can account for this. If we assume that formal GDP's elasticity with nightlight emissions is α (estimated to be 0.03), and the one between informal output and nightlights is $\chi\alpha$, we can translate Equation (3.5) into units of nightlights and calculate the implied growth rate of shadow economy output y^s, again up to the scale parameter ϕ^s.

$$\begin{aligned} nl^t_{s,t+h} - nl^t_{s,t-1} &= \phi^s(nl^s_{s,t+h} - nl^s_{s,t-1}) + (1-\phi^s)(nl^f_{s,t+h} - nl^f_{s,t-1}) \\ &= \phi^s \frac{1}{\chi\alpha}(y^s_{s,t+h} - y^s_{s,t-1}) + (1-\phi^s)\frac{1}{\alpha}(y^f_{s,t+h} - y^f_{s,t-1}) \\ (y^s_{s,t+h} - y^s_{s,t-1}) &= \frac{\chi\alpha}{\phi^s}\left[(nl^t_{s,t+h} - nl^t_{s,t-1}) - \frac{1-\phi^s}{\alpha}(y^f_{s,t+h} - y^f_{s,t-1})\right] \end{aligned} \tag{3.6}$$

We calibrate χ to be 0.18, which we consider a lower bound and calculate the implied shadow economy growth rates for different levels of ϕ^s. Notice that because formal output growth $(y^f_{t+h} - y^f_{t-1})$ is only observed at the state level, we cannot do so for each district. We then run our IV local projections with this measure directly, plotting the path of shadow economy output after a 1% credit supply increase due to the gold price in Figure E1 in Appendix E. The estimates are expectedly lower in this case, but still statistically significant, as is shown in Table E1, and for the first three years larger in absolute terms than the ones estimated for formal GDP. If the true ratio between the elasticity of the shadow economy and emissions of light is larger than 0.18, which we consider plausibly, then the negative effects will be more pronounced.

Censoring of nightlight emissions data Another familiar limitation of night light emissions as a proxy for total economic activity is that the strength of each pixel is limited to a value of 63, creating a plateau for how much an economy can grow according to this measure. This is particular the case for cities and districts/states that largely consist of urban areas. Even though only a handful of districts in our sample have values of night light emissions less than 10% from the maximum, the growth rates at high values might still be less well measured at high values. Since the problem is more pronounced to the end of the sample, we repeat the exercise excluding all years after the fiscal year of 2012/13. The respective results are all contained in Appendix Section E. Indeed, the estimated elasticity between light emissions and formal output is now considerably larger, namely 0.05 instead of 0.03. At the same time, however, the structural elasticities of credit supply on formal and informal y remain largely unchanged: The initial contraction of total economic activity becomes smaller in absolute size but statistically significant, and the (negative) point estimates for later horizons tend to be more pronounced. The implied path of cumulative shadow economy growth shows clearly negative values one and two years into the shock, after which it begins to grow again moderately.

VIIRS-DNB We provide another robustness test with a different measurement technology for total economic activity. The Visible Infrared Imaging Radiometer Suite's

(VIIRS) Day-Night Band (DNB) provides globally a dataset of nightlight visibility that is more sensitive and thus allows to improve the measurement of nightlight emissions relative to DMSP-OLS. Using the VIIRS sensor we construct separate indices for each district, state and respective fiscal year. Despite its higher precision, this data comes at the cost of only being available from 2012, reducing the time-variation of the sample to only 6 years (or 5 for 1-period growth rates). Nevertheless, even in this data we confirm the central insight from the full panel, namely that the shadow economy tends to shrink in response to a credit supply expansion. Appendix E contains, first, the updated elasticity between log changes of nightlight emissions in a state and its GDP growth rate. Due to the higher sensitivity, this is now higher, namely around 0.2 and thus closer to Henderson et al. (2012). If we regress formal output on the log nightlight index directly, including a fixed effect, the elasticity is even higher. We proceed as in the baseline and run local projections of horizon-specific changed of the scaled nightlight index (y^f) on changes of log real credit (c), using the same instruments. The coefficients are less precisely estimated, but the response of nightlight output in years 1 and 3 are firmly negative nonetheless. In Figure E3 we again compute the elasticity of the shadow economy with respect to higher credit supply implied by Equation 3.5. The result is in line with our baseline estimates, although the effect seems to be stronger in the medium run.

3.5 Conclusions

We have shown that after a sudden availability of credit, total economic activity as measured from outer space does not expand to the degree that we would expect given GDP growth. As a consequence, we conclude that the shadow economy shrinks considerably, with an elasticity that can even be lower than -1 in the medium run. While estimations with different measures of nightlights and for different time periods come to slightly different conclusions with respect to the magnitude and timing of the effect, they all agree that the shadow economy contracts with the availability of credit.

We have used a novel combination of data to disentangle the relationship between credit, output and formalization. Geocoded data on nightlight emissions was used to estimate total, formal and informal, economic activity, and bank credit is available for each district. We have exploited heterogeneity of credit availability in India both over time and across districts. The source of exogenous variation was provided by the price of gold, a commodity which has a special place in the Indian society both as a symbol and storage device of wealth, but also as a means to obtain liquidity when needed. We have shown consistently that an increase in the global gold price led to an expansion of credit in India. As a result, GDP expands. We have used local instrumental variable projections to estimate and display the dynamic effects of such a credit cycle: As credit becomes easier to obtain (for both households and firms), real output grows, generating better conditions to obtain more credit and invest more. The medium-run elasticity of the official GDP figures with respect to our gold price shock are between 0.1 and 0.2.

It is against this backdrop that we find that the gain in GDP is to a large extent, if not completely or even more so, offset by decreases in the shadow economy. Measures of total economic activity fall. Negative estimates have been found previously in the literature and can be rationalized by a higher incentive to formalize business dealings to obtain credit from banks. While credit is unavailable, the incentive to do so is low, but if it becomes more available under the requirement to declare income and wealth, resources are re-allocated from the informal to the formal sector. Our new causal evidence suggests that this re-allocation process, at least in the short run, has negative effects on total economic activity, and that the economy reaps the benefits from higher credit supply only with time.

APPENDIX

This Supplementary Material appendix provides greater detail on data sources and variables used in this chapter (Appendix Section A.1), discusses the impact of India on the gold price (Appendix Section B) and presents further robustness analyses (Appendix Section E).

A Data and methodological procedures

A.1 Variables and data sources

The following table presents a description of the variables used in this chapter.

Variable (Source)	Description
Administrative divisions (GADM)	The data on boundaries of states and districts is from GADM version 3.6, released in 2018, which can be accessed at [https://gadm.org]. During the time span considered the outer borders of India remain unchanged, inner administrative divisions on the other hand changed, e.g. carving out of new states and districts for example the foundation of the state Telangana in 2014. These changes are expert coded and matched to the timing of when the Reserve Bank of India adjusted their data aggregation reporting on district-level bank lending and borrowing.
Bank deposit and credit (RBI)	Publicly available data from the Quarterly Statistics on Deposits and Credit of Scheduled Commerical Banks, RBI. Digitised since 2003q4, older series between 1998q4 until 2003q2 is available as pdfs, that we digitised for this study. *Bank credit*: End-of-quarter credit outstanding from all bank branches in each district. *Bank debit*: End-of-quarter deposits at all bank branches in each district. *Number of offices*: The number of bank branches that constitute the total number of reporting offices per district on the individual level balance sheet statistics, quarterly.
Bank lending rate (IMF Monetary, Financial Accounts)	Measured as the average lending rate by scheduled Indian banks per fiscal year. The bank lending rate spread is calculated as the spread between the average bank lending rate and the central bank's deposit rate.
Consumer price index	Nominal variables are deflated using the national consumer price index retrieved from the St. Louis Fed (mnemonic INDCPIALLQINMEI)
District area (authors' calculation)	Calculated as the extent in square kilometres of each district over time, accounting for area changes in case a new district is carved out from an existing one.
Exchange rates, EUR/INR, USD/INR	Measured as nominal exchange rate changes of the Indian rupee INR with respect to the Euro EUR and the US Dollar USD.
Gold price (St.Louis Fed)	Gold prices in US dollar per Troy ounce (London afternoon fixing), deflated by the value of the consumer price index CPI at the end of each fiscal year.
GDP/Formal economic activity (RBI)	The formal economic activity in India is measured as log difference of the Gross Domestic Product, GDP, at the state level. The data is from RBI statistics.
GDP (CHN, EU, US) (St.Louis Fed)	To control for confounders in global gold price movements, GDP measured as log differences for China, Europe and the United States is included. The time series is from the St. Louis Fed.

(continued on next page)

Variable (Source)	Description
Muslim population (Census 2011)	The share of people registered as Muslim at the state level. The data is taken from the Population Census 2011, which is accessible at: [https://www.census2011.co.in/religion.php]. Due to a later founding date, the state Telangana is not considered here.
Nightlight / Total economic activity (NOAA, World Bank)	Total economic activity is measured using the fiscal yearly sum of monthly averages of daily nighttime satellite imagery of all the pixels within each district's boundaries. The data, is from the project Light Every Night, LEN, published by the World Bank in collaboration with the National Oceanic and Atmospheric Administration (NOAA), the University of Michigan and New Light Technologies, sourced from the NOAA National Centers for Environmental Information (NCEI) archive. We are using the imagery from the Defense Meteorological Satellite Program Operational Linescan System (DMSP-OLS) sensor. The data has a spatial resolution of ca. 4.9km at night, and the digital values range from no light at 0, to full light at 63 (a low 6-bit quantization).
Population (Census 2011)	Calculated as the representative number of people living in each state. The data is taken from the Population Census 2011, which is accessible at: [https://www.census2011.co.in/states.php]. According to the data, the most populated state is Uttar Pradesh with a population of 199.6 millions, and the least populated is Sikkim with 610577 people.
Population Density (GPWv4)	Calculated as the mean density of population in each district and state of the sample. The data, from the Gridded Population of the World Version 4 (GWPv4) models the global human population on 30 arc-second grid-cells based on population census tables and cartography, which can be accessed at [https://doi.org/10.7927/H49C6VHW]. The estimates used are from the year 2015.
Repo rate RBI (RBI)	Annual average of the repo rate at which RBI lends to commercial banks
Silver price (St.Louis Fed)	Silver prices in US dollar per Troy ounce (London afternoon fixing), deflated by the value of the consumer price index CPI at the end of each fiscal year.
Statutory liquidity ratio, SLR (RBI)	Regulatory ratio of specified securities bank must maintain in relation to liabilities
Stock prices (various sources)	Stock returns are measured for India using the NIFTY50, for the US using the S&P500 and the VIX index.

B Aggregate time series

B.1 Do developments in India affect the gold price?

The gold price can only be a relevant instrument for credit supply in India if it does not itself reflect news about the Indian economy. Because India is a major consumer of gold, this is not per se clear. We draw on daily stock market returns to assess this hypothesis, because gold is a liquid traded commodity and thus a direct link between shocks in India and the global gold price would most easily be detected in high frequency data. In particular, we download daily close data of Standard & Poor's Nifty, which is the benchmark stock market index representing 50 Indian companies. We do the same for the gold price, the S&P 500 and the VIX index of implied volatility as an index of global uncertainty.[17] Returns are calculated as log differences with respect to the previous day where all four series are observed. For the VIX, we calculate the difference of absolute values. Table B1 shows determinants of the global gold price, starting from news about the Indian economy as reflected in the Indian stock market index.

Table B1: Determinants of gold

	ΔGold$_t$		
	Baseline	incl. global variables	incl. 3 lags thereof
ΔNIFTY$_t$	0.035***	0.039***	0.043***
	(0.009)	(0.009)	(0.009)
ΔS&P500$_t$		-0.035*	-0.026**
		(0.020)	(0.012)
ΔVIX$_t$		-0.008	0.002
		(0.014)	(0.002)
Observations	5884	5884	5881
R^2	0.002	0.003	0.006

Notes: Regressions of log difference of daily gold price on log difference of daily stock returns for India (NIFTY50), U.S. (S&P500) and the VIX index for implied volatility as a proxy for uncertainty. Sample: 1995-2019. Significance levels: *** 1% ** 5%, * 10%.

The estimated coefficient is positive and statistically significant, but very small. It implies that a 1.5% increase of the value of the Indian stock market – which is the standard deviation of daily returns in the respective period – is associated with a 0.05%

[17] Data sources: Historical index data for the NIFTY 50 is downloaded from the National Stock Exchange of India. Daily gold prices and VIX quotes are downloaded from the Federal Reserve Bank of St. Louis database (mnemonics GOLDAMGBD228NLBM and VIXCLS), and the S&P 500 is draws from Yahoo finance (GSPC).

Table B2: Results with residualized gold price

	$c_{d,t+h} - c_{d,t-1}$				
Gold, residualized II	$h = 0$	$h = 1$	$h = 2$	$h = 3$	$h = 4$
$\Delta\widetilde{G2}_t$	0.107	0.257***	0.339***	0.422***	0.479***
	(0.072)	(0.087)	(0.114)	(0.139)	(0.139)
Observations	11557	10860	10171	9511	8854
Districts	697	689	660	657	652
R^2	0.16	0.29	0.39	0.30	0.31
Gold, residualized III	$h = 0$	$h = 1$	$h = 2$	$h = 3$	$h = 4$
$\Delta\widetilde{G3}_t$	0.107	0.258***	0.334*	0.419	0.477***
	(0.071)	(0.086)	(0.112)	(0.139)	(0.139)
Observations	11557	10860	10171	9511	8854
Districts	697	689	660	657	652
R^2	0.16	0.29	0.39	0.30	0.31

Notes: Local projections as in Table D1, gold price purged for information effects from Indian and U.S. stock markets and global uncertainty. Significance levels: *** 1% ** 5%, * 10%.

increase in the gold price. The standard deviation of daily changes of the gold price is 1.07%. Consequently, it explains a miniscule fraction of the variation in daily gold price changes. Therefore, we can say that the gold price we use as an instrument for credit supply in India is likely not determined by news about the Indian economy that might jointly affect the price of gold and domestic credit supply. The coefficient on the U.S. stock market index is negative, confirming the role of gold as a hedging commodity that typically appreciates in value when stock markets depreciate. At the same time, however, we do not find any statistical relationship between the VIX and the gold price. Even when additionally including lags of the explanatory and the dependent variables in the last columns of Table B1, we only find a very low R^2, stressing the lack of predictability of gold price changes and the suitability as an external instrument for the purpose of our identifying our credit supply shocks.

Nevertheless, we proceed to clean the gold price shock from the small variation that could be explained by conditions in India as reflected in stock prices, and calculate a counterfactual gold price filtering out the explanatory factors from the first two columns in Table B1, respectively. We refer to the residuals gold price shocks as $\widetilde{G2}$ and $\widetilde{G3}$, respectively. As expected given the small explanatory power in Table B1, the results shown in Table B2 are virtually unchanged.

B.2 A Proxy-VAR for credit supply in India

We estimate a macro-financial vector-autoregressive model of the Indian economy and use innovations in the gold price to identify a credit supply shock. Let Y be a vector of the following the variables: The log level of real GDP, our preferred quarterly measure of (formal) economic activity. The second variable is the amount of credit to the non-financial private sector outstanding at the end of the quarter, divided by the nominal GDP deflator. Ultimately, we include the spread between the average lending rate (as reported in the IMF Monetary and Financial Accounts) and the central bank's deposit rate. We estimate the following model:

$$Y_t = \alpha_0 + \alpha_1 t + A(L)Y_{t-1} + u_t \tag{7}$$

$A(L)$ is a function of parameters in the the lag operator; we include 4 lags. The reduced-form residuals u_t are a linear combination of the underlying structural shocks $u_t = S\varepsilon_t$.[18] Instead of recursively identifying the ε's, we use the change in the gold price as an instrumental variable z to exogenously shift variables on impact. This Proxy-VAR approach was pioneered by Gertler and Karadi (2015).

Let s denote the (1×3) vector corresponding to each variable's contemporaneous response to a structural credit supply shock ε^s. This response cannot be explained by other observables, such that they feed into the model's reduced-form residuals:

$$u_t = s\varepsilon_t^s$$

Let further z_t be a vector of externally obtained innovations in an instrumental variable that is correlated with ε^s. One can then, in a first step, isolate the variation in one series of reduced-form residuals u_t^s attributable to the instrument series z_t by computing fitted values of the following OLS regression:

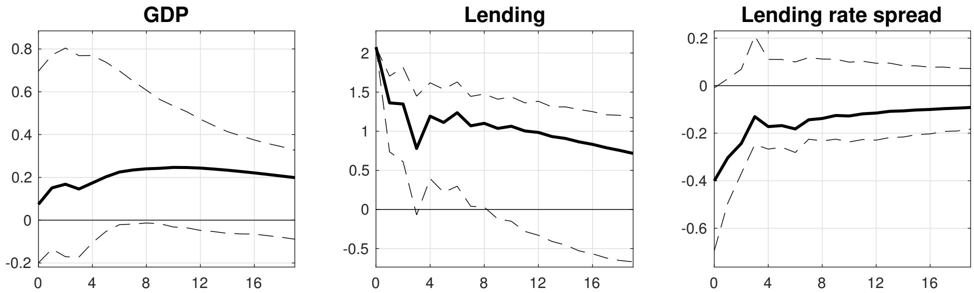
$$u_t^s = \beta z_t' + \zeta_t$$

The second step is to relate the other residuals u_t^q to those fitted values using

$$u_t^q = \frac{s^q}{s^s}\hat{u}_t^s + \xi_t.$$

[18] Ω is the variance-covariance matrix of the reduced-form residuals. We can identify them by Cholesky decomposing the matrix into $E[SS'] = \Omega$. The lower-triangular S implies recursiveness assumptions: Economically, one restricts structural shocks not to have a contemporaneous impact on variables that are ordered before. Depending on the variables included, this can be hard to justify.

Figure B1: VAR impulse response functions



Notes: Quarterly impulse response functions of a three-variable Proxy-VAR. A credit supply shock is identified using innovations in the traded gold price as an instrument on the reduced-form residuals of the aggregate amount of lending. 90% confidence bands are based on Wild bootstrapping where residuals are multiplied with a random draw from the Rademacher distribution. Sample: 1996q2-2019q4.

Because any variation in $\hat{u}_t^s$ is due only to ε_t^s, this will consistently estimate the reaction of all other variables to ε_t^s, and allows to identify s^q up to the scalar s^s.

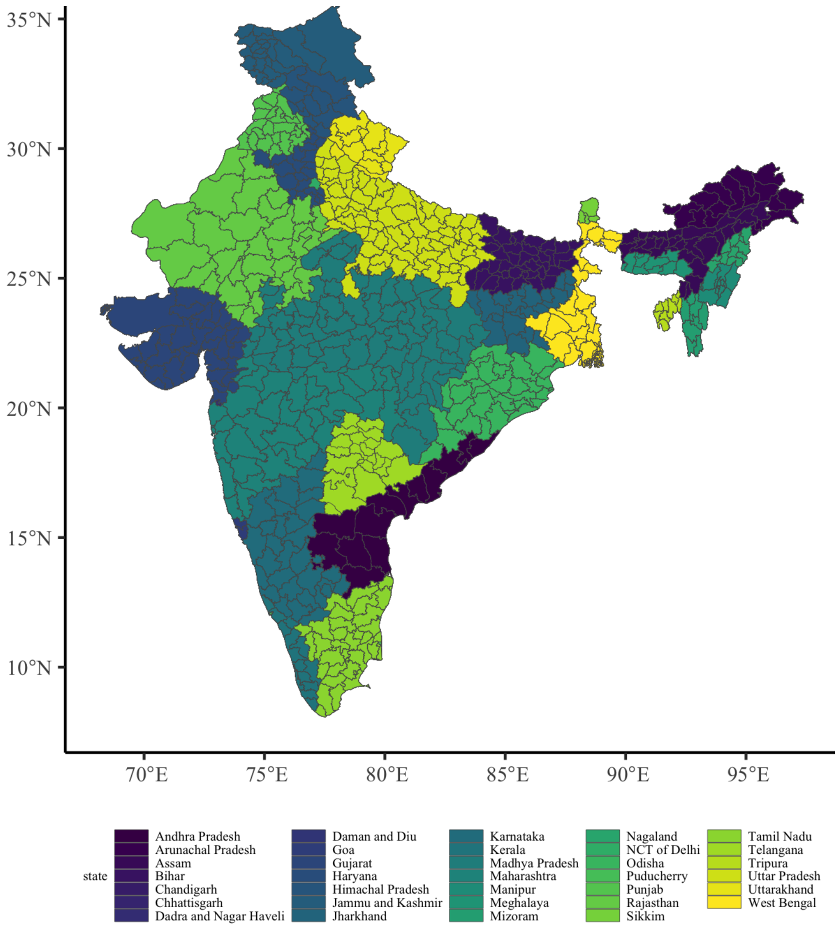
This setup allows us to test if the expansionary effect of our gold price instrument on the Indian economy works even in the aggregate. We use as z the log difference of the end-of-period traded gold price. The first stage of the IV regression reveals that over the sample period used (1996q2-2019q4), a shock of the size of one standard deviation increases bank lending by 1.8% above what is accounted for by the vector-autoregressive process. At the same time, we find evidence that the interest rate on those loans decreases at least temporarily, reinforcing our confidence in that the gold price can act as an instrument for exogenous innovations in credit *supply*, be it through the bank lending or borrower balance sheet channel.[19]

The first panel of Figure B1 further highlights that the eased credit conditions have an expansionary effect on GDP. Registered national economic activity increases between 0.2 and 0.3%, and both magnitudes and persistence are broadly in line with evidence from the US (Mumtaz et al., 2018).

[19] Piffer and Podstawski (2018) use changes in the oil price around certain geopolitical events as a proxy for uncertainty shocks. The advantage is that the gold price is purged from any movements that might be affected by developments in India. Due to the few events during the rather short sample period, these shocks do not yield significant results in our data, even though the point estimated are qualitatively similar.

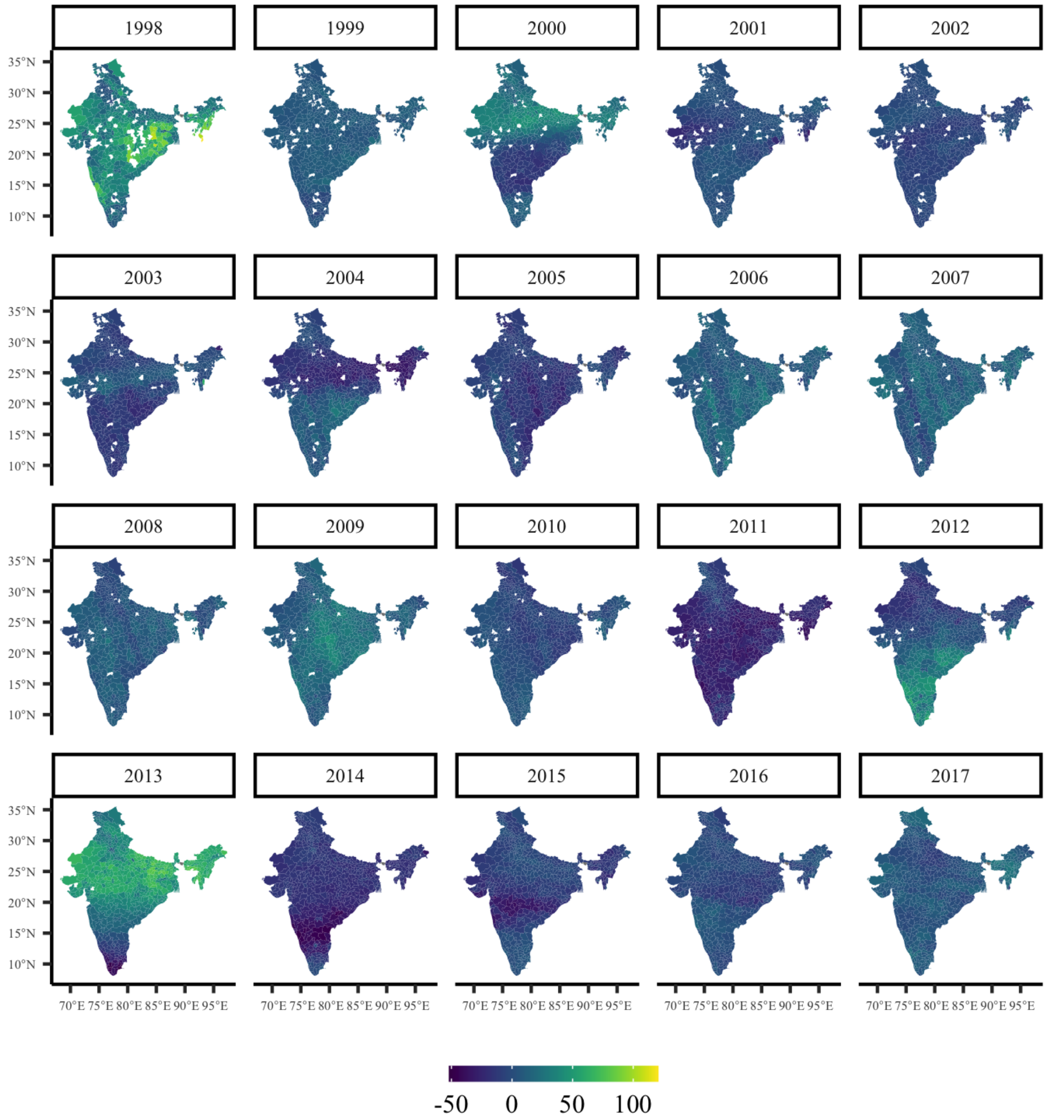
C Additional figures

Figure C1: States and Union Territories with districts as subdivisions



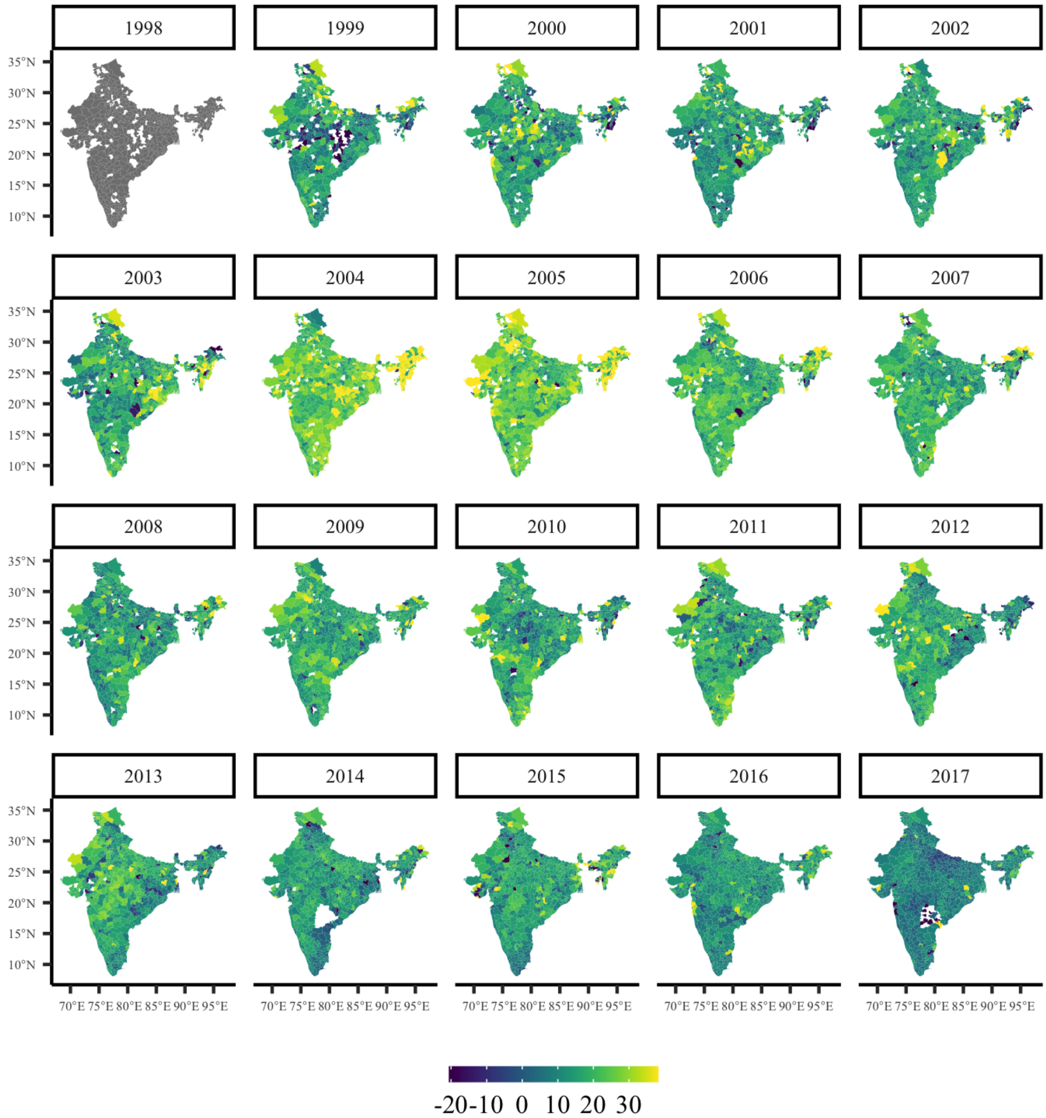
Notes: The figure shows the 28 States and 6 Union Territories with district subdivisions as of 2017

Figure C2: Log growth rates in nighttime light emissions for each district in India between fiscal years 1998 and 2017



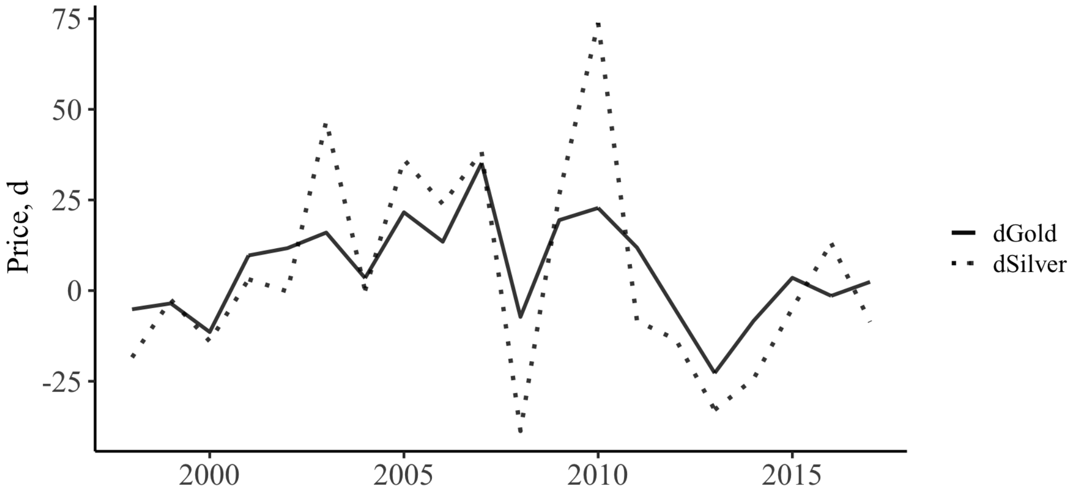
Notes: The figure displays log differences in average nightlight emissions observed from space

Figure C3: Log growth rates in bank lending for each district in India between fiscal years 1998 and 2017



Notes: The figure displays log growth rates in total bank lending per fiscal year over the period 1998 and 2017. There is no data available for 1997, hence no changes observed for the fiscal year 1998. The formation of new districts leads to unobservable growth rates for certain states, districts over time, e.g. the formation of the state of Telangana in 2014.

Figure C4: Time series of gold and silver price



Notes: The figure shows the global gold and silver price at the yearly frequency.

D Additional tables

Table D1: Baseline first stage local projections

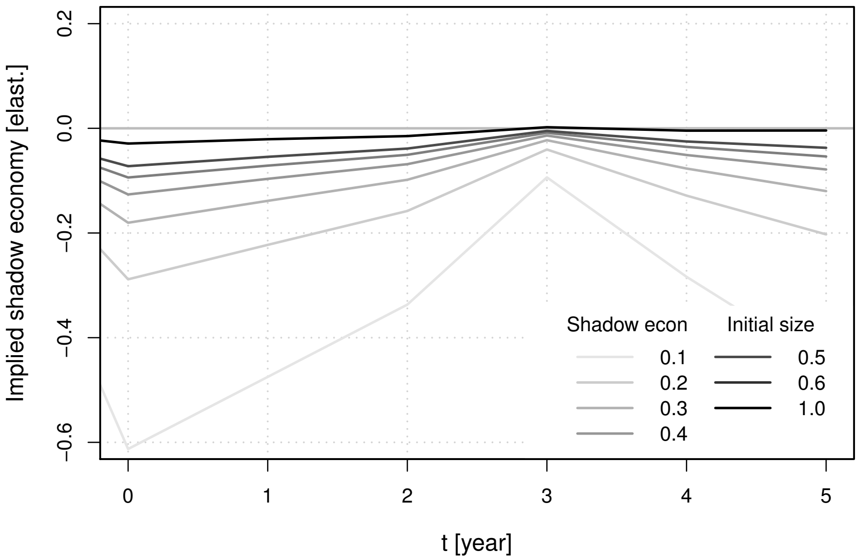
	$c_{d,t+h} - c_{d,t-1}$				
	$h = 0$	$h = 1$	$h = 2$	$h = 3$	$h = 4$
ΔGold_t	0.111	0.253***	0.338***	0.432***	0.469***
	(0.069)	(0.096)	(0.125)	(0.151)	(0.154)
Observations	11557	10860	10171	9511	8854
Districts	697	689	660	657	652
R^2	0.16	0.29	0.38	0.30	0.36

Notes: Local projections of credit outstanding by district and fiscal year on changes of the gold price in the respective time period (Equation 3.3). Control variables: lagged gold price change, contemporaneous change in SLR and repo rates and global control variables. Standard errors are clustered by fiscal year and district. Sample: 1999-2017. Significance levels: *** 1% ** 5%, * 10%.

E Additional results and robustness

E.1 Shadow economy estimates when they have a lower elasticity with nightlight emissions

Figure E1: Credit supply and the shadow economy: Structural elasticities by initial ϕ^S



Notes: Elasticity of the shadow economy with respect to credit supply expansion when it is estimated directly using Equation (3.6). Following La Porta and Shleifer (2014), we assume that the shadow economy's elasticity with respect to nightlight emissions is only 0.18 of that of formal GDP. Sample: 1999-2016.

Table E1: IV local projection estimates with direct estimate of informal output growth

	$y^s_{s,t+h} - y^s_{s,t-1}$				
	$h = 0$	$h = 1$	$h = 2$	$h = 3$	$h = 4$
$c_{s,t+h} - c_{s,t-1}$	-0.288**	-0.223***	-0.158***	-0.040	-0.129***
	(0.139)	(0.046)	(0.020)	(0.058)	(0.023)
Observations	479	452	425	398	371
States	27	27	27	27	27
First-stage F-stat.	4.48	11.04	91.93	59.68	68.94

Notes: Local projections of implied shadow economy growth rates by state and fiscal year on changes of credit instrumented with the following variables: $\Delta\text{Gold}_t, \Delta\text{Gold}_t \times \text{Mughal mints}_s, \Delta\text{Gold}_t \times \frac{\text{Credit}_{s,t-1}}{\text{Deposits}_{s,t-1}}$. The dependant variable is constructed using Equation (3.6). Following La Porta and Shleifer (2014), we assume that the shadow economy's elasticity with respect to nightlight emissions is only 0.18 of that of formal GDP. The measure is only defined up to the share parameter of initial informality, which we set to $phi^s = 0.2$ for illustrating purposes. Inference statistics are robust to alternative measures. Control variables: lagged gold price change, contemporaneous change in SLR and repo rates and global control variables. Standard errors are clustered by fiscal year. Sample: 1999-2016. Significance levels: *** 1% ** 5%, * 10%.

E.2 Subset of pre-2012 data

Table E2: GDP and night lights: Pre 2012

	$y^f_{s,t} - y^f_{s,t-1}$		$y^f_{s,t}$	
	Mean intensity	Sum	Mean	Sum
	(1)	(2)	(3)	(4)
$nl_{s,t} - nl_{s,t-1}$	0.054***	0.048***		
	(0.008)	(0.010)		
$nl_{s,t}$			0.041	0.044
			(0.036)	(0.038)
State fixed effect	No	No	Yes	Yes
Observations	459	459	460	460
States	31	31	31	31

Notes: Columns (1) and (2) show regression outputs of the growth rate of statewide GDP and night light emissions. (3) and (4) do the same in log levels, including a constant for each state. (1) and (3) take the mean intensity of pixels in a state, (2) and (4) the sum. Standard errors are clustered by state. Sample: 1999-2012. Significance levels: *** 1% ** 5%, * 10%.

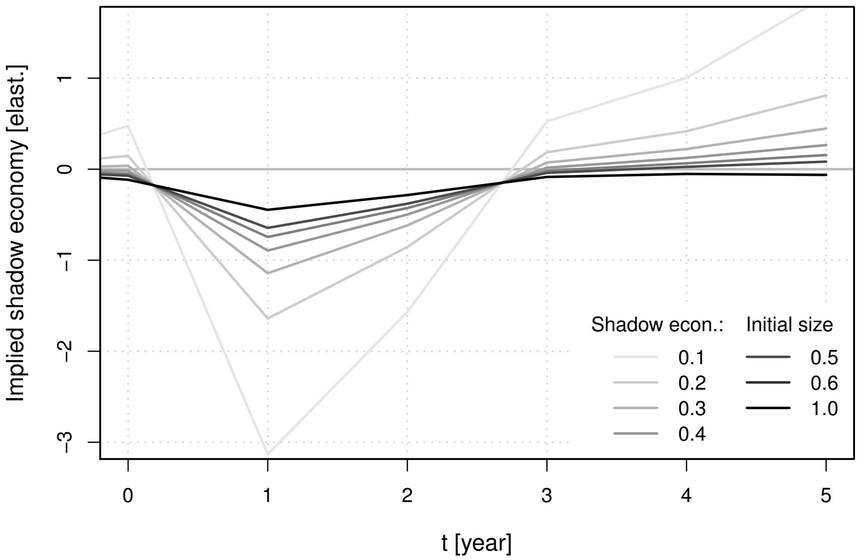
Table E3: Baseline IV local projection estimates (Pre 2012)

	$y^f_{s,t+h} - y^f_{s,t-1}$				
	$h = 0$	$h = 1$	$h = 2$	$h = 3$	$h = 4$
$c_{s,t+h} - c_{s,t-1}$	0.182**	0.148***	0.142***	0.153***	0.169***
	(0.085)	(0.049)	(0.031)	(0.031)	(0.050)
Observations	443	443	443	443	442
States	32	32	32	32	32
First-stage F-stat.	5.57	25.22	123.37	114.15	33.21

	$y^t_{d,t+h} - y^t_{d,t-1}$				
	$h = 0$	$h = 1$	$h = 2$	$h = 3$	$h = 4$
$c_{d,t+h} - c_{d,t-1}$	-0.116*	-0.446**	-0.284***	-0.085*	0.052
	(0.070)	(0.175)	(0.088)	(0.045)	(0.041)
Observations	8232	8251	8242	8250	8238
Districts	629	634	634	634	634
First-stage F-stat.	47.84	4.84	16.97	102.94	161.26

Notes: Local projections of log GDP differences (upper panel) and scaled total economic activity (lower panel) by state and fiscal year on changes of credit instrumented with the following variables: ΔGold_t, $\Delta\text{Gold}_t \times \text{Mughal mints}_s$, $\Delta\text{Gold}_t \times \frac{\text{Credit}_{s,t-1}}{\text{Deposits}_{s,t-1}}$. Control variables: lagged gold price change, contemporaneous change in SLR and repo rates and global control variables. Standard errors are clustered by fiscal year. Sample: 1999-2012. Significance levels: *** 1% ** 5%, * 10%.

Figure E2: Credit supply and the shadow economy: Structural elasticities by initial ϕ^S (pre 2012)



Notes: Elasticity of the shadow economy with respect to credit supply expansion implied by estimated of GDP and total economic activity (Equations 3.4 and 3.5). Sample: 1999-2012.

E.3 Alternative measurement of total economic activity (post 2012)

Table E4: GDP and night lights: Post 2012 with VIIRS

	$y^f_{s,t} - y^f_{s,t-1}$		$y^f_{s,t}$	
	Mean intensity (1)	Sum (2)	Mean (3)	Sum (4)
$nl_{s,t} - nl_{s,t-1}$	0.196***	0.197***		
	(0.034)	(0.036)		
$nl_{s,t}$			0.359***	0.332***
			(0.104)	(0.110)
State fixed effect	No	No	Yes	Yes
Observations	126	126	123	123
States	31	31	31	31

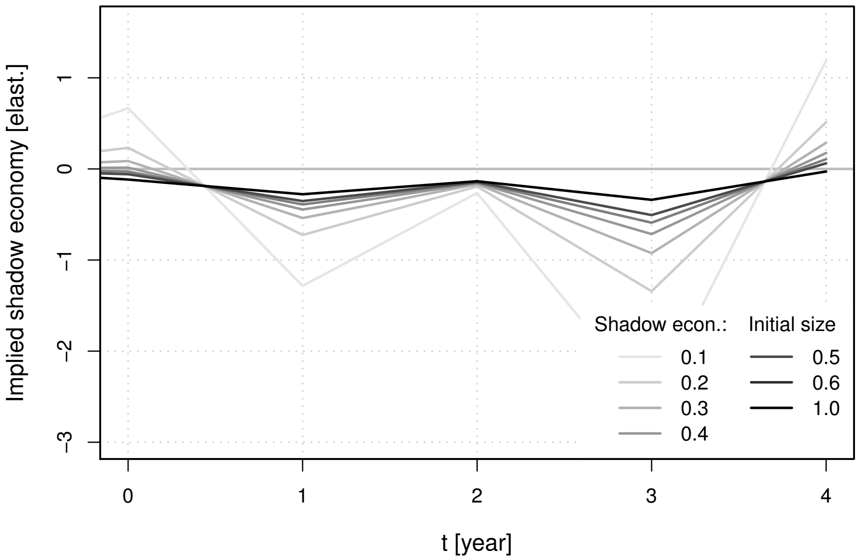
Notes: Columns (1) and (2) show regression outputs of the growth rate of statewide GDP and night light emissions. (3) and (4) do the same in log levels, including a constant for each state. (1) and (3) take the mean intensity of pixels in a state, (2) and (4) the sum. Standard errors are clustered by state. Sample: 1999-2012.
Significance levels: *** 1% ** 5%, * 10%.

Table E5: Baseline IV local projection estimates (Post 2012 with VIIRS)

	$y^t_{d,t+h} - y^t_{d,t-1}$				
	$h = 0$	$h = 1$	$h = 2$	$h = 3$	$h = 4$
$c_{d,t+h} - c_{d,t-1}$	-0.116	-0.278***	-0.135	-0.339***	-0.028
	(0.288)	(0.049)	(0.141)	(0.061)	(0.258)
Observations	3237	2590	1949	1303	672
Districts	654	654	648	640	637
First-stage F-stat.	47.84	4.84	16.97	102.94	161.26

Notes: Local projections of scaled total economic activity by state and fiscal year on changes of credit instrumented with the following variables: $\Delta\text{Gold}_t, \Delta\text{Gold}_t \times \text{Mughal mints}_s, \Delta\text{Gold}_t \times \frac{\text{Credit}_{s,t-1}}{\text{Deposits}_{s,t-1}}$. Total economic activity is approximated using the VIIRS data only. Control variables: lagged gold price change, contemporaneous change in SLR and repo rates and global control variables. Standard errors are clustered by fiscal year. Sample: 2013-2017.
Significance levels: *** 1% ** 5%, * 10%.

Figure E3: Credit supply and shadow economy: Struct. elast. by initial ϕ^S (post 2012 with VIIRS)



Notes: Elasticity of the shadow economy with respect to credit supply expansion implied by estimated of GDP and total economic activity (Equations 3.4 and 3.5). Total economic activity is approximated with an alternative measurement technology of nightlight emissions. Sample: 2013-2017.

Conclusion

In the first chapter, I considered conflict dynamics in the context of peace agreement negotiations and the conclusion of a deal. In an effort to further the understanding of non-state military actor's behaviour in light of negotiations' incentive structures, I matched at the actor level conflict data with the agreement data. This novel data sets allows me to exploit the panel structure of individual actor, grid-cells and monthly frequency in a difference-in-difference design. As such I can assess peace agreements in space and across time. I distinguish between first and last agreement signed to try to limit the influence of spillover effects from temporally and spatially intersecting agreements. I find that peace agreement signature is associated with a reduction in violence in the first and last agreement signed. In the former it found suggestive evidence that it is driven by ex ante dominant conflict locations with measurable impact on newer ex post locations. In the case of last agreements an overall reduction is found.

The understanding of the effect of peace negotiations on signatory actors, non-signatory actors and society at large is relevant, not least as successful peace designs have a large societal benefit.

In the second chapter, co-authored with Stefano Tripodi, we look at an agricultural shock caused by desert locusts in 2014 in Ethiopia. To measure the welfare effect on subsistence farming households in rural Ethiopia, we model the movement of these animals exploiting their passive flyer nature allowing them to behave like air particles in NOAA's HYSPLIT model. Not only to we improve the measurement of flying insects economic shock, we account for potential non-random exposure to exogenous shocks accounting for area shock propensities. We found looking at a smaller outbreak of locusts that agricultural output measured in kilograms is 11% lower , and while we find no effect on children on average, the results suggest with increasing exposure intensity that weight-for-height and BMI are negatively impacted.

As desert locusts are predominately caused by environmental extreme situations, their appearance given the destructive capacity remains of heightened concern for the future.

In the third chapter, co-authored with Gabriel Züllig, we consider the role of credit in explaining the size and dynamics of the shadow economy in India. Challenged by the possible endogeneity and the fact that economic activity in the shadow is difficult to observe, we exploit global gold prices as a source of exogenous variation that plays a crucial role of collateral in the Indian economy. The latter problem we address by using nighttime lights. Using district-level credit data, we find that a 10% increase in the gold price leads to a 1.5% increase in credit in the short run. Furthermore, we estimate a structural elasticity with respect to credit supply between 0.1 and 0.2.

The informal sector accounts for a large share of the economic activity and provides incomes for billions of people, thus understanding mechanism to foster formalisation effectively directly policy relevant.

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