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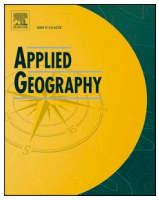

A convergence research approach to resolving 'wicked problems': Lessons from an interdisciplinary research team in land use science

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A B S T R A C T

Many contemporary social and environmental problems are increasingly 'wicked.' Convergence research offers an effective approach to tackle wicked problems by integrating diverse epistemologies, methodologies, and expertise. Yet, there exists little discussion of *how* to develop and employ a convergence research approach. This article describes our collaborative research efforts to achieve convergence research and team science. For over a decade, we have sought to understand how drug trafficking activities, and the counternarcotics efforts designed to thwart them, catalyze catastrophic changes in landscapes and communities. We first discuss how understanding our wicked problem called for epistemological convergence of diverse data through a team science approach. We then unpack the potential insights and challenges of methodological convergence by drawing upon examples from our land cover and land use change analysis. Third, we argue that the nature of complex, pressing problems requires convergence research to be politically engaged and accountable to the multiple communities affected. This article aims to provide research teams insight into how to pursue epistemological and methodological convergence while attending to the inherent politics of producing knowledge about wicked problems.

1. Introduction: converging, but how?

Many contemporary social and environmental problems are increasingly 'wicked'. Wicked problems are those that have no clear definitions or solutions, intersect multiple and often contested societal values, are often perpetuated by the interventions intended to solve them, and have unforeseeable consequences across spatial, temporal, and governance scales (Rittel & Webber, 1973; Levin et al., 2012; Mertens, 2015; DeFries & Nagendra, 2017). Wicked problems arise from the dynamics of inherently complex systems with many interconnected components, which can produce large and surprising responses to small perturbations or interventions (DeFries & Nagendra, 2017). Pressing wicked problems include climate change and biodiversity loss (DeFries & Nagendra, 2017; Levin et al., 2012; Spapens & Huisman, 2016), the global refugee crisis (Raadschelders et al., 2019), and urban sustainability (Goodspeed, 2015) to name a few. As many scholars point out, science and management have developed to efficiently address narrowly focused, well-bounded, or in other words, 'tame' problems (e.g., DeFries & Nagendra, 2017; Levin et al., 2012; Medin et al., 2017; Rittel & Webber, 1973). However, new approaches are needed that are at least as diverse and adaptive as the wicked problems they seek to solve (Ackoff, 1979; Medin et al., 2017).

Convergence research offers a potentially effective approach to tackle wicked problems. According to the National Science Foundation's Growing Convergence Research program,[1] convergence research is driven by 1) pressing and complex societal problems and 2) deep integration of knowledge, methods, and expertise from different disciplines to catalyze 3) new ways of conducting science. Convergence research intentionally integrates seemingly disparate epistemologies, methodologies, and expertise in a way that enables asking and answering research questions that would not have previously been possible. However, while some guidance for defining and conceptualizing convergence research exists (e.g., Angeler et al., 2020; Cannon, 2020; Peek et al., 2020; Roco, 2020), the authors are not aware of any exposition of the convergence

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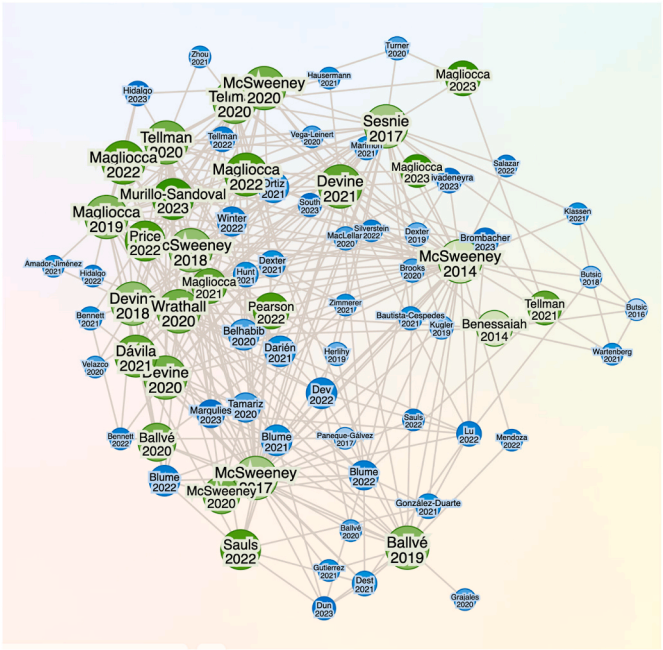

Fig. 1. Research network by Research Rabbit using the 30 papers in our team science network with the 50 papers most relevant to our network, since the McSweeney et al., 2014 publication with our team in green, and other papers in blue. Size of dot colored by connectivity to other papers in the network, and color is by recently (lighter is older). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

research *process,* which can be challenging to achieve. In this article, we identify key challenges and pathways for successful and sustained convergence research, by drawing upon illustrative examples from a long-term, evolving, and inter- and trans-disciplinary research team.

This paper sketches our experience with convergence research and team science as a research collective tackling a wicked problem over the past decade. Specifically, we sought to understand how drug trafficking activities, and the counternarcotics efforts designed to thwart them, can together catalyze catastrophic changes in the landscapes and human livelihoods through which the drugs pass. We, the authors, are core members of a research team - or perhaps a research 'cloud' - that has pursued this problem over time, with the essential contributions of other members who have come and gone—a total of some 50 different participants. In effect, we are a research cloud as much as a research team. We measure the success of our 'team science' in terms of 1) the questions that we have been able to satisfactorily articulate and answer, 2) our contributions to an emergent research area, 3) the broader impacts we have had on drug policy other policy spheres, and non-profit organizations engaged in communities in the region, and 4) the researchers that have been trained and been promoted in their careers through their work with us. Another measure of our success is that new questions continue to emerge leading research internal and external to our group in new directions. To the extent that we have been successful, we credit our organic, convergence research approach. In this paper, we lay out what a convergence approach may look like and key components that we considered transferable to other topics.

We first discuss our wicked problem from a diversity of research perspectives to familiarize the reader with the issues and key insights that framed our convergence research. Next, we discuss challenges in achieving epistemological convergence through a team science approach. In the fourth section, we unpack the potential for methodological convergence by drawing on examples from our research experience. Finally, we argue that the nature of wicked problems requires convergence research to be politically engaged and accountable to the multiple communities affected by the multifaceted problems we study.

2. The socio-environmental consequences of narco-trafficking as a wicked problem

Research challenges, like ours, are 'wicked' because there is no obvious solution to them, either methodologically or in terms of policy response. For example: how do we measure and visualize clandestine and/or illegal phenomena? How can we access and process presumably classified information about overseas militarized law enforcement? Possible solutions are equally unclear. The United States' prevailing solution to the illegal cocaine trade has relied on interdiction of cocaine shipments between South American production zones and North American consumer markets. This strategy has consistently seized less than 10% of the total supply (McSweeney, 2020b) and motivated the expansion of highly profitable narco-trafficking to an operational area greater than 7 million mi^2 (Magliocca et al., 2022). Furthermore, US and international counter narcotics intervention has had a strongly destabilizing effect for Central and South American countries.

Multiple, contested societal values guide intervention strategies designed to address wicked problems. Critics of U.S. drug policy point to the multi-decade failure of the War of Drugs to reduce supply, use, and abuse of illicit drugs (Rydell et al., 1996; Caulkins & Reuter, 2010; Paterson & Robinson, 2014; Pollack & Reuter, 2014). The volume of cocaine moving annually north through Central America has for the past decade typically exceed 1000 MT/year, peaking at 2500 MT in 2016–2018, and cocaine prices in the U.S. continue to fall while purity increases (McSweeney, 2020a; UNODC, 2020). Proponents of current strategies counter that interdiction efforts are important for decreasing the total volume entering the U.S., are vital for deterring narco-trafficking activities in specific places and have the symbolic and moral values of stopping criminals (GAO, 1994; Kelly, 2016). However, recent moves to decriminalize or legalize coca production and/or consumption of many drugs, such as in Portugal, Uruguay, and potentially Colombia (Caulkins, 2017; Hall et al., 2018; Kahn, 2023) challenge the inevitability of the current probationary paradigm.

In terms of policy, was our aim to offer recommendations for *improving* law enforcement, or abolishing it? This latter question highlights the degree to which we engaged with a 'hot-button' social issue, with *contested views* on how to address the illicit drug problem. Those social tensions were manifest among our group members. For us, that included the ethical dilemmas associated with simply studying the problem: would we be revealing criminal activities in ways that would put our friends and colleagues at risk? Would we potentially contribute to the ongoing demonization of Central America as a constellation of failed states? And those were just the problems we anticipated prior to beginning research, as many others emerged.

For our wicked problem, and many others, unforeseeable, and unintended consequences of interventions abound. Counterdrug interdiction has had the unintended consequence of spreading and fragmentating trafficking routes—known as the "balloon and cockroach effects," respectively—into new and more numerous locations (Bagley, 2013; Magliocca et al., 2019; Mejia & Restrepo, 2016). This expansion includes impacts such as narco-fueled violence and corruption (Bunck and Fowler, 2015), infusion of unparalleled amounts of cash and weapons (McSweeney et al., 2018; McSweeney, 2020a), dispossession and seizure of land from rural communities (McSweeney et al., 2017; Devine et al. 2018, 2020), and extensive and rapid environmental destruction (Sesnie et al., 2017; Tellman, Sesnie, et al., 2020; Wrathall et al., 2020; Devine et al., 2021). Furthermore, increased risk of interdiction increases the profit available to traffickers, which capitalizes illicit and licit activities all along the cocaine supply chain (McSweeney et al., 2018; Devine et al., 2020; Magliocca et al., 2021; Murillo-Sandoval et al., 2023).

Given the complexity and messiness of this wicked problem, our early attempts to gain scientific traction produced only partial

explanations, exposed numerous knowledge gaps, and raised more research questions than answers. Rather than deterring further research investment, these conditions proved to be essential for fostering a convergence research approach. In the remainder of this article, we share our insights and often hard-learned lessons by ***highlighting the key lessons*** learned for achieving convergence research and team science approach.

3. Epistemological convergence: the challenges of wicked problems

Each discipline approaches our wicked problem differently. For example, operations research approaches the problem of disrupting illicit activities from the perspective of supply chains, emphasizing quantitative understandings of supply chain structures and operational dynamics (e.g., Altner et al., 2010; Keskin et al., 2022). Typical analytical solutions are focused on optimizing the location and intensity of interventions to disrupt flows (Curtin et al., 2010; Keskin et al., 2021; Price et al., 2022). Political economy and ecology perspectives view the drug trafficking problem through the lens of power asymmetries that create marginalized and vulnerable rural communities and landscapes, which are exploited by narco-traffickers to evade counterdrug interventions driven by larger geopolitical regimes (McSweeney et al., 2017; Devine et al., 2018; Massé & Margulies, 2020; Blume et al., 2022). Understandings of how and why drug trafficking is impacting certain locations rely on discourse and policy analyses and grounded explanations derived from field observations and ethnographies (Davis & Sauls, 2017; Devine et al., 2021; McSweeney, 2020b). Distinctly, economic perspectives focus on the price structures and transaction costs associated with different phases on the drug trafficking supply chain (e.g., Caulkins & Reuter, 1998; Caulkins & Reuter, 2010; Dávila et al., 2021; Pearson et al., 2022), whereas remote sensing approaches can search for spatio-temporal signatures of land-use change in dense time series stacks of satellite imagery that can be indicative of illicit activities (Sesnie et al., 2017; Tellman, Sesnie, et al., 2020; Murillo-Sandoval et al., 2023).

In this section, we lay out the process by which our network of interdisciplinary researchers evolved over time, and along the way, learned to integrate diverse epistemologies and methods. Epistemological convergence entails engaging with and even integrating these multiple perspectives, experiences, and viewpoints of the problem to produce new insights. This is a tall order; but perhaps rather than a starting point, it is goal to work towards, a reflexive process rather than a pre-condition. We flag two components of our experience that enabled and illustrate epistemological convergence. These include 1) team building and 2) integrating often conflicting epistemologies that define what constitutes data, knowledge, rigor, and validity in diverse ways.

3.1. A converging team

As with all wicked problems, no clear definition exists. Each

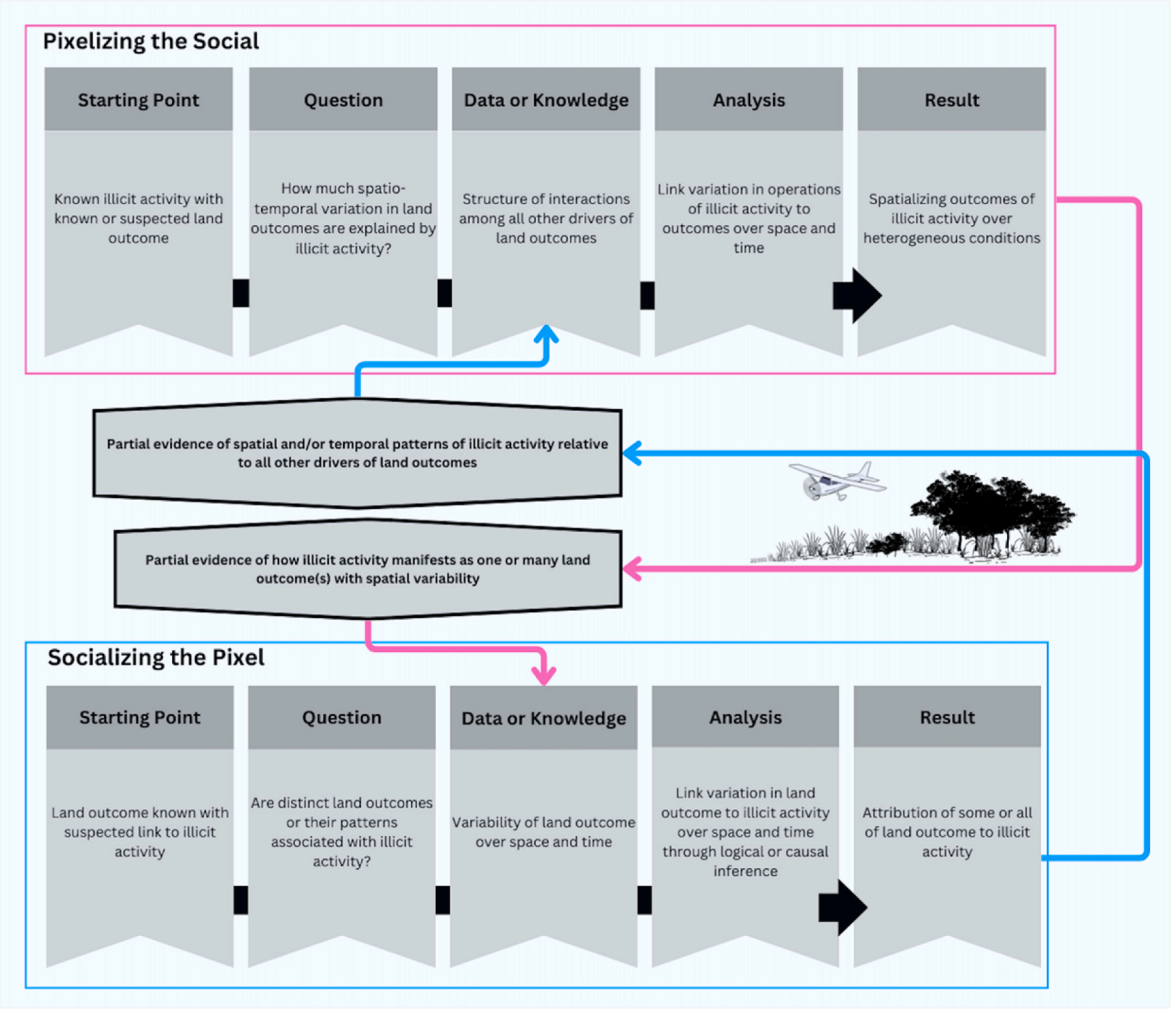

Fig. 2. Interacting approaches to 'pixelizing to social' or 'socializing the pixel' to leverage remote sensing analyses and complementary knowledge for studying the role of illicit transactions in causing land-use change (Tellman, Magliocca, et al., 2020). Reused with authors' permission.

researcher within our team may describe our problem differently. However, across our 30+ published articles, we wrestled with the fundamental challenge of measuring and explaining socio-environmental outcomes when the processes creating them are explicitly designed to be hidden. We endeavored to understand how cocaine trafficking during the War on Drugs has resulted in socio-environmental harms and landscape transformations in Central America, but the processes we investigate are global. Within this research program, it has been relatively easy to describe socioecological change—that is, to measure rates of deforestation, to document and describe land and resource dispossession, resource enclosure, extreme violence, and corruption in all areas of land and resource governance. The 'wicked' challenge has been to: a) determine causal relationships between socio-ecological change and specific illegal activities; b) estimate how illegal activities can themselves become a response to counternarcotic efforts; c) to build on those insights to offer recommendations for U.S. policy reforms needed to reduce harm. This challenge, by its very nature, led the founding team members (geographers and land-use scientists) to seek out and add scholars across different disciplines for domain and methodological expertise, which ultimately led to a convergence research team.

The emerging concept of convergence research draws from and informs more established frameworks of team science, interdisciplinary research (IDR), and transdisciplinary research (TDR). Team science is a collaborative research approach that addresses scientific challenges by combining the strengths and expertise of professionals trained in different fields and methods (Stokols et al., 2008; Ledford, 2015; Hall et al., 2018). Tenets of team science (Milojevíc 2014; Henson et al., 2020; National Research Council, 2015) include a high diversity of membership, deep knowledge integration, an aligned shared goal, a geographically dispersed and changing team composition, and high task interdependence.

Convergence research enables the conceptualization of previously intractable problems from novel perspectives (e.g., drug policy as an environmental conservation issue; McSweeney et al., 2014), deep integration of knowledge domains needed to address the problem drawing upon local stakeholder and/or Indigenous knowledge systems, adapting existing methodologies to novel and/or disparate problem areas, and generation of policy-relevant science (Angeler et al., 2020). Because convergence often entails entirely new combinations of knowledge domains and perspectives (Peek et al., 2020), achieving deep integration also requires more effort and intentionality than IDR and TDR to cultivate links between diverse knowledge domains, methodologies, research teams, and knowledge-producers.

Our research team was formed around an inherently compelling problem and societal need, which fulfilled the first of National Science Foundation's (NSF) criteria for convergence, but meeting the second criteria of deep integration across disciplines required years of workshops. We began by networking among researchers who were noticing changes in field sites across Central America in Panamá, Costa Rica, Nicaragua, Honduras, El Salvador, and Guatemala. Without meeting, we wrote a scoping paper for *Science* that attracted the attention of drug plicy reformers, including Open Societies. They funded two multi-day meetings that allowed us to map out the contours of the problem. We distinguished the need to understand pattern and the need to focus on underlying processes. That meant bringing together land change scientists with anthropologists, geographers, political scientists trained in very different traditions: positivist, post-positivist, feminist, post-structural, and Marxian. We acknowledged but were not ready to resolve this epistemic complexity. Consequently, our research products remained in disciplinary ruts, either in remote sensing or human geography journals, not both. Our team is not alone; many collaborative or interdisciplinary efforts retreat to disciplinary corners when philosophical differences arise such as when biological/ecological sciences and human dimensions meet (Grace et al., 2021) (see Fig. 1).

Achieving epistemological convergence for our team required meeting two to three times per year for several years, thanks to a grant from the National Socio-Environmental Synthesis Center (SESYNC). SESYNC's mission is to bring together the natural and social sciences to solve problems at the human-environment interface through data, methodological, and knowledge synthesis (Palmer et al., 2016). To support team science and IDR, SESYNC grants provide research groups, like ours, with high-tech collaborative spaces and exposure to a set of core practices informed by the science of team science to "facilitate team development of shared conceptual frameworks and provide customized support for teams that have challenging methodological, computational, or group dynamic issues" (Palmer et al., 2016: 111).

Non-conventional types of funding are needed to facilitate team science. To allow shared values, goals, methods, and epistemologies to emerge takes bringing geographically dispersed individuals together to think and work on collaborative activities for which funding can be hard to find (Arnott et al., 2020). Our team's SESYNC experience contributed two critical advances toward convergence. First, one of SESYNC's core practices is direct facilitation of team development with increasingly lighter interventions as needed as the project progresses. Crucially, SESYNC staff brought contributory and interactional expertise to our group meetings (Bammer et al., 2020; Collins & Evans, 2008). Contributory expertise included both 'knowing-that' a diverse team was necessary to make connections between seemingly disparate phenomena of the cocaine trade and land-use change and recognizing the need to add team members with 'know-how' expertise to bring methods and processes to integrate diverse team perspectives. This required interactional expertise to understand the diverse needs and perspectives of the disciplines involved without having necessarily been trained in any of them (Bammer et al., 2020). The team meetings at SESYNC became a vehicle for growing the collaborative team by adding members that did not necessarily have the depth of knowledge or understanding of the specific problem, but rather had highly complementary skills and expertise that broadened the possible avenues of inquiry.

Second, the act of ***meeting repeatedly, in-person, and over several years was essential for development of our shared goals, epistemological and methodological frameworks, and research agendas*** (Poteete et al. 2010). These extended, face-to-face meetings gave us the time and intellectual space to debate, compromise, and build a working interdisciplinary language (Buyalskaya et al., 2021; Palmer et al., 2016) through explaining and re-explaining our perspectives, continuously justifying or rethinking critical assumptions, and ultimately come to a shared understanding of the problem and ways to approach it. Two further advances toward convergence were achieved in this setting. ***Our repeated interactions in this dedicated physical and intellectual space fostered a team culture for open-mindedness*** to the value of other forms of knowledge and a willingness to tolerate intellectual discomfort outside of our disciplinary norms. This enabled us to focus on solving the problem at hand rather than falling back into more comfortable lines of inquiry that would likely be limited to advancing disciplinary knowledge. ***Effective communication strategies are essential to enable team science to work, as well as longer term time commitments by the team members*** (Graef et al., 2021; Love et al., 2022; Palmer et al., 2016). While this approach has been rewarding, it also created friction at times, particularly for early career scholars needing to demonstrate their productivity, and with current institutional, disciplinary, and/or sponsor incentive structures, which may not accommodate the slow, iterative process conducive to convergence research.

Additionally, as the initial phase in developing an agent-based model of the narco-trafficking network (Magliocca et al., 2019), we created a conceptual framework describing the logic for where, why, and how narco-traffickers sought to control and transform land in the process of transporting cocaine shipments throughout Central America. This framework served as an essential boundary object to concretize our various perceptions of the problem that we could collectively challenge or accept (Akkerman & Bakker, 2011; Palmer et al., 2016; Star, 2010). Notably, agent-based models have previously been identified as

potentially useful boundary objects due to their requirement to formalize diverse explanations of human behavior (Reilly et al., 2018; Steger et al., 2021). A boundary object is data or information, such as field notes, oral histories, or maps, used in different ways by different epistemic communities for collaborative work to translate knowledge across epistemic differences (Star, 2010).

This process made clear the ***equal need for researchers with grounded, lived experiences of the communities and landscapes being investigated and those that were more removed and could identify systematic regional similarities and differences***. As a boundary object, this conceptual framework also became a space in which each regional expert could situate their own experiences relative to a broader narrative of the entire Central American 'transit space'. For example, our broader conceptual framework clarified that instances of clandestine infrastructure creation in Panama, illegal cattle ranching in Guatemala, and dispossession of peasant and indigenous lands in Honduras, where all related to narco-traffickers' *modus operandi* to control land and territory for logistical purposes (Tellman et al., 2021).

3.2. Converging diverse epistemologies through the development of a data pedigree system

Given the complex, multi-scale nature of our research problem, we were forced to develop a means to integrate multiple independently produced data sources, each with their own biases and partial perspectives collected at different periods, by different organizations, using various acquisition technologies, standards, and specifications (Devillers et al., 2007; Fischer et al., 2023). However, we first needed to reconcile diverse epistemological values among our research team about what constituted rigorous and meaningful data and how/whether some information should be prioritized over others. ***To achieve such epistemological convergence, we borrowed an approach from data science, namely data pedigree systems, to assess the quality and appropriateness of a wide range of data*** – from precise and authoritative observations to informed guesses (Costanza et al., 1992; Funtowicz & Ravetz, 1990). Data pedigrees are a user-centered approach to data quality assessment and integration (i.e., fitness-for-use'), which balances standardization with expert knowledge of the contingent nature of the data's source and meanings (Devillers et al., 2007; Fischer et al., 2023; Wentz & Shimizu, 2018). Generally, criteria such as data reliability, completeness, and spatial, temporal, and/or technical applicability with the research topic are used to score the quality of the data for a given purpose (Magliocca et al., 2025; Schmill et al., 2014). Importantly for achieving epistemological convergence, data pedigree systems can accommodate both 'absolute' (e.g., data completeness, accuracy) and 'relative' (e.g., data reliability, representativeness) data quality considerations.

The first step in developing the data pedigree system was to conduct internal team interviews to solicit perspectives about which data sources were most reliable and/or important for providing insight into the spatial and temporal dynamics of narco-trafficking operations. For example, positivists among the team tended to emphasize the importance of geographic clarity for comparing data sources. *Geographic Clarity* assessed the agreement between a data source's geographic representation of the event or location of narco-trafficking activity and its consistency with the geographic characteristics of the data-generating process being measured (e.g., a specific drug and/or property seizure represented by a latitude and longitude coordinates) (Magliocca et al., 2025). Conversely, postpositivist team members tended to place more weight on data *Provenance*, which assessed the reliability of the data source considering knowledge of the geographic context of the event or observation and/or source of data generation. For example, data sources that were reported second-hand (e.g., foreign news media reports) or relied on voluntary reporting of narco-trafficking activity could be subject to political or law enforcement activity biases that can lead to under- or over-reporting narco-trafficking activity (Magliocca et al., 2025). Finally, team members that were more familiar with the causal inference techniques that would be used in subsequent analyses prioritized accurate temporal information as the most important data quality characteristic.

The second step in the development of the data pedigree was a series of heuristic decision trees that were iteratively developed to related deep qualitative understandings of data quality with quantitative, standardized scores. All datasets were individually scored and then mapped to a common, spatially grided data framework which accounted for uncertainty of each source (see Magliocca et al., 2025, for details). The resulting data pedigree system produced standardized, spatially explicit scores that made highly disparate data sources interoperable and balanced the priorities of team members from different epistemological backgrounds.

Only through combining and integrating different data and epistemologies from our diverse perspectives and methodological toolkits can we obtain the clearest understanding of illicit economies impact on environmental change in Central America and elsewhere. For many of us, integrating these partial datasets and perspectives challenged assumptions and biases inherited through our disciplinary training. Team science approaches encouraged us to remain somewhat agnostic about individual analytical frameworks, reflexively recalibrate our epistemological assumptions, and remain open to different methods and ways of knowing.

This approach is not a one size fits all. Some individuals and disciplinary approaches are unwilling to be flexible enough to suspend their own assumptions and methodological commitments to meet other perspectives on equal footing. To achieve convergence requires ***aligning of values and the identification of a shared goal and purpose,*** **as well as** ***excellent communication skills and members ability to compromise.*** This process is slow, which contradicts the temporal pressures facing scholars. For example, the project put one team member at risk because their dissertation chapter relied on generating a rapid indicator of narcotrafficking at higher spatial and temporal resolution than the official data provided, and the team's first attempt to generate one based on members scoring narcotrafficking intensity based on their contextual failed; the variance across members' perceptions in the same geography was too large to support statistical modeling. Leadership from senior scholars on the team was required to intervene and rally members around a compromise and new innovative solution—transferring the narcotrafficking metrics and applying them to a codebook to analyze news media. Since the team had no new grants to generate a news media database, individual members used existing funds to each take on one country in Central America. The media database supported the dissertation project and became a foundational dataset still used in team research (e.g. Magliocca et al., 2025; Tellman, et al., 2020; 2021) and a protocol was established for attribution and permission in future uses of the co-produced dataset. When appropriate and feasible, however, team science and convergence research can catalyze new ways of knowing wicked problems as well as new ways of studying them, and help junior scholars launch high impact articles and careers. To mitigate risks, ***we recommend including a mix of scholars (junior to senior) in convergence science to try new approaches but be prepared to fund second or third attempts if the first method fails.***

4. Methodological convergence: understanding wicked problems

From the outset, we faced daunting empirical challenges. To scale up country specific case-study insights meant finding ways to measure and map drug trafficking activities at a regional scale. But how could we 'see' the ephemeral passage of cocaine through remote landscapes? And arguably more difficult still: how could we map and measure the counternarcotic efforts that preceded and followed it? After all, drug traffickers do not publicize their activities or the geographic space they occupy. US defense, intelligence, and law enforcement communities

(who share counternarcotic duties in the Western Hemisphere) typically classify all data on the timing and specifics of their activities, whether in Central America or elsewhere.

4.1. Converging data

Studying wicked problems like ours requires methodological convergence. Data and knowledge gaps are pervasive in the study of wicked problems (DeFries & Nagendra, 2017) and the clandestine nature of narco-trafficking exacerbates this situation. Federal and other agencies poorly monitor the effectiveness, tradeoffs and cost/benefit ratio of drug enforcement or market responses to policy interventions. Causal inference about licit activities can generally be achieved from one or two disciplinary perspectives, which likely produce an incomplete, but still sufficient, explanation. But that is not the case for illicit activities (Tellman, Magliocca, et al., 2020). Studying narco-trafficking demands the creative integration of multiple data, sources, and methods to render the invisible visible.

Data scarcity and the danger of collecting potential existing data requires pragmatism rather than methodological purity. Being forced to work with incomplete or consolidated data means parsing together partial perspectives from remote sensing analysis, media analysis, and ethnographic interviews. Data consolidation often means combining disparate sources that may lack study design features such as devising a representative sample either through random or systematic approaches. Sampling availability and detection bias are unaccounted for without methods to resolve these issues. Nevertheless, wicked problems such as climate change or organized crime effects on human and animal populations ***require new ways of consolidating and synthesizing data, often from overlooked sources*** (e.g., media reports and other data that may have once been considered outside the scientific domain).

Two key features of our convergence approach positioned us to respond to this challenge. First, we are a methodologically diverse team of researchers that possess training in political and critical geography, human-environment geography, geographic information science and technology, spatial ecology, remote sensing, computational social science, and complex systems science. We have applied methods including ethnography, geospatial data analytics, critical discourse analysis, agent-based and land change simulation modeling, global value chain analysis, causal inference, spatial statistics, and remote sensing time series analysis. Second, while many of these methodological approaches are common in IDR, their deeper, intentional, and adaptive integration (i.e., convergence) was greatly facilitated by guidance from 'socializing the pixel' and 'pixelizing the social' heuristics (Geoghegan et al., 1998). Rooted in abductive reasoning, these approaches can use both inductive and deductive analytical methods to adjudicate among alternative hypotheses to arrive at the best explanation (Walton, 2014). It was critical to adopt such an approach in the context of limited knowledge or observations of clandestine phenomena from which only partial explanations would be possible if our analyses were constrained to either inductive *or* deductive methods.

Briefly, 'pixelizing the social' attempts to render information about a social process (often qualitative) into a spatially explicit framework that can be related and integrated with contextual (i.e., biophysical conditions) information derived from remote sensing analysis. In contrast, 'socializing the pixel' brings social process information to bear on the explanation of remotely sensed spatial patterns (Geoghegan et al., 1998). Originating with remote sensing-based analysis of land-use change, we embraced a broader conceptualization that requires methodological and epistemological plurality to adapt to whatever partial knowledge and data sources were available to answer the question at hand.

4.2. Pixelizing the social and socializing the pixel

As presented in Tellman, Magliocca, et al. (2020), 'pixelizing' and 'socializing' approaches can be iteratively and synergistically leveraged to strengthen causal inference in situations where limited knowledge and/or data prevent clear causal attribution of landscape changes or do not provide sufficient insights into the processes generating spatial patterns of change. Given knowledge about how a social process is operating, a 'pixelizing' approach can produce partial evidence of how a social process may manifest spatially explicit land cover change patterns over heterogeneous conditions.

Alternative hypotheses are formed about how the social process could lead to varying spatial patterns and landscape change outcomes over time. Data are collected on contextual and causal factors related to all plausible pattern-generating processes (e.g., legal and illicit activities). Data could be in the form of grounded ethnographies, survey, and national census data, and/or social simulation model output. Causal inference and correlation methods (e.g., regression) provide partial inferences into how outcomes vary as the consequence of the variables operating in socially, politically, and environmentally heterogeneous conditions. For example, recently Costa Rica has become a strategic location for moving drugs to Europe, which may show up differently than what has been observed in other countries. These analyses can identify or quantify the likely variation in landscape outcomes of the social process of interest *relative* to alternative causes (i.e., inference by process of elimination), but the exact location or amount of the social process of interest cannot be directly ascertained.

In contrast, the 'socializing' approach starts from a firm understanding of the spatial pattern of landscape changes that are known or likely associated with the social process of interest, but a less clear understanding of the underlying causal mechanism for land use decisions that evoke larger-scale landscape changes. Data about the spatial patterns of changes may come from remote sensing analyses, participatory mapping, or landscape simulation model outputs, whereas knowledge about the social process may come from empirically based hypotheses and theory, or ethnographic and other expert knowledge. Knowledge of the social process is used to estimate likely landscape outcomes of that process over space and time, and empirical inference methods estimate the location and extent of landscape changes that can be causally attributed to some or all the processes of interest. Importantly, 'pixelizing' and 'socializing' approaches are most powerful when used when complementary data and analyses are synthesized together and their respective data to arrive at valid conclusions (see Fig. 2).

In our experiences studying narco-trafficking, the partial insights gleaned from 'pixelizing' provided critical knowledge inputs to 'socializing' analyses and vice versa. For example, this group's early inquiries into the narco-trafficking phenomenon started with a 'pixelizing' approach relying on remote sensing-based analyses of landscape change to estimate the effects of narco-trafficking. Multi-sited ethnographies by several team members identified recurrent patterns of narco-trafficking related land dispossession accompanied by unusual locations, sizes, and rates of forest loss. This was the lead on a potential *modus operandi* that produced a discernible spatial signature. Based on these insights, Sesnie et al. (2017) isolated the spatio-temporal signal of 'anomalous deforestation' patches, which were cleared at large extents and rapid rates beyond what legal land users (e.g., smallholders) could feasibly manage as swidden agriculture. We then successfully acquired province-level estimated cocaine flows and seizures data in the Consolidated Counterdrug Database[1,2] (CCDB) (McSweeney, 2020a) from the White House Office of National Drug Control Policy (ONDCP), which allowed us to visualize and map illegal activities over time and test the space-time causal relationships between anomalous forest loss patches and cocaine flows.

Sesnie et al. (2017) found that cocaine trafficking could account for between 15% and 30% of annual national forest loss in Guatemala, Honduras, and Nicaragua from 2000 to 2014, and that loss was

[2] Available at: https://heima.ua.edu/data.html.

particularly concentrated (30%–60%) within nationally and internationally designated protected areas. Tellman, Sesnie, et al. (2020) refined this estimate by combining additional official cocaine seizure data sources of varying detail and reliability, with an assembled dataset from news media reports (from national newspapers) documenting specific instances of narcotrafficking activity. This dataset served as input into fixed effects panel regression models to estimate the proportion of forest loss explained by narco-trafficking relative to conventional drivers of deforestation (e.g., cropland and pasture expansion, population growth). Their analysis found that the timing and location of narco-trafficking activities explained an additional 5%–9% of all forest loss beyond conventional drivers (Tellman, Sesnie, et al., 2020). These findings empirically verified the phenomenon of 'narco-deforestation' across multiple countries. However, they could not provide insights into why narco-traffickers would impact landscapes in such a conspicuous way.

With evidence that narco-trafficking was producing unique spatial patterns of deforestation, we turned to a 'socializing' approach to understand why. Relying on multi-sited ethnographies and reviews of investigative reports, grey literature, and related academic works, we gained a deeper understanding of why and how narco-traffickers sought to control and transform land. The political-economic logics and grounded processes underlying the transformation of rural economies through illicit capital became clearer (McSweeney et al., 2017), as did how narco-trafficking's presence undermined conservation governance, and how exploitation of marginalized populations led to disproportionate forest loss in protected areas and indigenous territories (Devine et al., 2018; Tellman et al., 2021; Wrathall et al., 2020). Additionally, concepts from global commodity chain analysis (Gereffi et al., 2005; Neimark et al., 2016) prompted us to consider how rent was captured differently along the cocaine supply chain (McSweeney et al., 2018; Dávila et al., 2021; Magliocca et al., 2021). This was our impetus to assemble estimates of differences in wholesale cocaine prices throughout Central America to explain why land-use change from illicit capital was likely more intense were greater rents could be captured (Pearson et al., 2022).

In addition to improving our understanding of narco-deforestation dynamics, synthesizing grounded knowledge of how narco-trafficking controlled land and transformed rural economies led us, in a sense, back to where we started – U.S. drug policy. We hypothesized that narco-traffickers' presence in some of the most remote and biodiverse landscapes of Central America was primarily an adaptive response to pressure from counterdrug interdiction activities. We understood what conditions were favorable for narco-trafficking operations and how those produced discernible spatial signatures of deforestation, but the causal link to a supply side counterdrug policy was not yet clear. This motivated us to expand our collaborative team and broaden our information gathering to Government Accountability Office reports, direct communications with counterdrug interdiction practitioners (e.g., ONDCP, U.S. Southern Command), and an on-site visit with the entity coordinating all counterdrug activities, the U.S. Joint Inter-Agency Task Force – South (JIATF-S), to learn more about counterdrug interdiction operations. Building upon the knowledge described above, our new insights into counterdrug interdiction were formalized into a spatially explicit simulation model of the co-evolution of narco-trafficking networks and counterdrug interdiction operations (Magliocca et al. 2019, 2022). Using an abductive experimental design, this 'socializing' approach successfully replicated many historical trafficking trends and captured the spatial dynamics describing how drug trafficking organizations respond to interdiction efforts. A subsequent 'pixelizing' approach used this insight into narco-traffickers' adaptive responses to interdiction to estimate the shifting 'suitability', or attractiveness, of Central American landscapes in before and after peak interdiction pressure in each location (Magliocca et al., 2022). This analysis was able to link the adaptive spatial behavior of narco-traffickers to spatial patterns of disproportionate use of nationally designated protected areas and indigenous territories following interdiction pressure.

The interplay between inductive and deductive, 'pixelizing' and 'socializing' approaches enabled stronger causal inference than any one approach was capable of alone, and importantly, did more than just "quantify" the effect of a driver, it could elucidate and describe mechanisms and functions in a complex socio-ecological system. Diverse and adaptive methodologies are critical in the context of addressing complex problems involving multiple dynamic and evolving social-environmental systems and illicit drivers of landscape change. As drug trafficking and its environmental consequences evolved in Central America, ***our research methodology evolved and adapted by necessity, always remaining methodologically flexible.***

5. Politically engaged and accountable research

We characterize our approach as accountable, public facing research, a term we use to foreground accountability to the people and places impacted by our work as well as a commitment to translating our research to diverse popular and policy-oriented audiences. Accountability means prioritizing the safety of people and their communities who are already impacted and at risk from drug violence and corruption, building alliances with grassroots actors and civil society, and accounting for the consequences of the knowledge and discourses we (re) produce.

Wicked problems are inherently political. Political does not just equate to the *de jure* world of politics and formal politics, but also to power relations and inequalities inherited from the past and often reproduced in the present (Markkanen, 2019). We could not, then, avoid ***addressing the ethics and politics of our work head-on***. Below we review how.

5.1. Ethical considerations

"Doing no harm," was a guiding principle of our work, but it could be hard to determine the boundaries of harm in communities suffering from both the actions of drug traffickers and the violence of the counter-narcotic response. We were particularly concerned that we might put our collaborators and interlocutors at risk by even talking with them about the dynamics of the cocaine trade. What we found, however, was that given our long-term relationships with affected communities, most residents we spoke with trusted us enough to share accounts of events and illegal business practices. In our published work, we protected their identities by never referencing them or their communities by name.

Our security concerns influence what we publish, how we publish, where we publish, and how we make policy recommendations. For example, when we geo-visualize narco-activity, like narco-deforestation (Sesnie et al., 2017) and other forms of narco-degradation (Devine et al., 2021), we use heat maps or kernel density maps rather than geo-referenced locations. We consistently ask ourselves if our publications, especially our maps and models, can be used by the military or police to target rural communities as havens of illegality. For example, in current research investigating the presence and agro-ecological potential for Central America coca cultivation (Murillo Sandoval et al., 2023), we decided against producing fine-scale coca cultivation suitability maps due to the potential that they might circulate and cause reputational or actual harm to rural people unlucky enough to live near organized criminal groups' coca production areas.

Our work consistently raises the question regarding what type of relationship we should have with counter-narcotic agencies (e.g., DEA, US Coast Guard, NGA, State Department) who monopolize data, fund research, and directly influence policy. For example, while we sought to directly critique the U.S.-led drug interdiction mission, that critique relied on working with employees of the US' Office of National Drug Control Policy, and later with an interagency agreement under the Southern Command, to access the data on cocaine movements that allowed us to marshall that critique (see McSweeney, 2020a). And the

authority that those data lent to our findings has been crucial for our access to spaces in which to share our work, including at the UN Office of Drugs and Crime (UNODC) Commission on Narcotic Drugs.

To navigate these fraught relationships, we rely on regular dialogue with our on-the-ground regional collaborators. We take cues from them about how and to what extent we might engage with powerful entities such as the U.S. State Department, and we are constantly humbled by their deep knowledge and agility in negotiating these forces. We also regularly communicate with Indigenous and peasant organizations managing the protected areas where we work about the socio-environmental problems they find most pressing, as well as to obtain interpretation and feedback of our work. Indeed, it was our pre-existing relationships with these groups that initially led us to study the drug war—a topic in which none of us had previous experience. In many cases, our friends and colleagues in Central America pushed us to speak out publicly about the processes transforming their lands and livelihoods because they could not.

We often ***share our research results and request feedback on tentative findings with our community partners*** and leaders to receive feedback on our analysis before publishing. Discussing our research with academics is one thing, but when we present and discuss our findings in communities it undergoes a kind of stress test, both empirically and politically. In this exchange, our interpretations are improved, we discuss security and political concerns, and our collaborators identify ways in which our science supports their multiple organization and community goals.

The nature of our wicked, data poor, and politically sensitive research necessitated that our team members ***use the feminist method of reflexivity (***England, 1994***) to understand how our data, methods, and knowledge are partial***, and our knowledge of our problem is "situated," Using reflexivity to think about how knowledge and power relations are situated in spatially and temporally specific ways means recognizing all forms of knowledge reflect the specific conditions in which they are produced, enabling certain insights while obscuring others (Haraway, 1988). We believe recognizing the politics and power relations baked into practices of knowledge production does not make research less objective or biased, although ignoring issues of power and politics certainly can. In practice, reflexivity for our team translates into discussions of vulnerability and privilege in our research and in dynamics of team science. To account for bias, or the partiality of perspectives, we triangulate interpretation and analysis between team members and our on the ground collaborators. We also create opportunities to discuss the power relations of our work with our in-country field experts in conference settings and on podcasts.

5.2. Policy implications of publicly engaged research

Why link drug policy to drug trafficking crimes to forest loss in the first place? When we began this work, in 2011, the fields of land use/land cover change/political ecology and drug-related criminology had few points of connection. Nor did many of us initially see any reason to link these disparate fields. But we were compelled to do so because our collaborators in Central America effectively urged us to investigate its emerging human and environmental impacts. Across many different sites—from Panama to southern Mexico—they insisted that drug traffickers were causing large-scale environmental damages, and that the US-led War on Drugs was making things worse.

Public facing research signifies a commitment to communicating analysis and findings across multiple audiences to maximize the broader impacts of our work. Members of our team have presented our analyses at the United Nations General Assembly on the World Drug Problem, at the UN Commission on Narcotic Drugs, at the U.S. Office of National Drug Control Policy, and to Indigenous and conservation groups across Central America. We have also spoken publicly about our findings in over 100 unique interviews with journalists for news media, radio, TV, and podcasts. Many of those interactions were inspired by work targeted at policy audiences (e.g. Magliocca et al., 2019; McSweeney, 2015; McSweeney et al., 2014; McSweeney et al., 2023). We have also been invited to be part of coordinated media campaigns in which members of our team have partnered with Indigenous and peasant organizations to in support of protected areas threatened by narco-capitalization of cattle ranching, oil palm, timber and wildlife poaching, and mining (Devine et al., 2021).

The opportunity to share work with popular audiences comes at a risk. One of the key policy narratives we uphold is to illuminate the devastating consequences of the War on Drugs for people and environments in Central America and elsewhere. Yet we have found it hard to 'control' that narrative: media reports often simplify the message, demonizing drug traffickers rather than the larger dynamics of the Drug War and tend to foreground standard 'law and order' approaches as the only solution. We have learned to refuse journalists requests unless they are willing to identify orthodox drug policy as a causal factor, and/or to highlight alternative approaches to supporting rural communities. For example, our policy work advocates for rethinking the problem of drugs in society as public health, public safety, governance, and environmental issues rather than a criminal justice one. Like many critics of the drug war, we advocate for reinvesting efforts and resources in policies that address the structural inequalities that enable organized crime to flourish, for example, programs that strengthen democratic institutions at the local level (Wrathall et al., 2020) and enable community-based management of land and resources in rural and protected areas (Devine et al., 2020).

6. Conclusions: a convergence research approach to wicked problems

This article has formalized our reflections from long-term analysis of illicit economies' contribution in global environmental change to provide examples of how and why to conduct convergence research and team science to address wicked problems. Our future research plans include examining how the drug trade intertwines with other illicit and licit economies, like the cattle ranching sector, as well as developing models that attribute land use and land cover change casually to cocaine trafficking.

We suggest achieving convergence is a process rather than a starting point and should emphasize at least three critical components. First, we submit that epistemological convergence is needed to study wicked problems because of the partiality of data, the multiplicity of perspectives, and complex socio-environmental systems that define wicked problems. Differences in philosophies may limit convergence approaches but may also inform or promote new avenues for investigation (Eigenbrode et al., 2007). Our experience developing a 'data pedigree system' (Magliocca et al., 2025) that integrates diverse cocaine trafficking datasets demonstrates that epistemological convergence is best achieved through team science practices that facilitate integration of different ways of knowing a wicked problem. Furthermore, epistemological convergence requires recognition of the partiality of different disciplinary viewpoints, and synthesis of those viewpoints into a more wholistic understanding. This is practically achieved by multiple in person workshops where conceptual diagrams are constructed, and trust is built (see Table 1).

Epistemological convergence enables the second component, methodological convergence. In our case 'socializing the pixel/pixelizing the social' methodology (Tellman, Magliocca, et al., 2020), we integrate

Table 1
Summary of our team's activities, insights and key lessons learned for each convergence research life cycle step.

Life Cycle Steps: Convergence Research	Case Study Outcomes: Socio-Environmental Impacts of Illicit Activities	Key Insights or Lessons
Conceptualize problems from novel perspectives	• Reconsided drug policy as an environmental conservation issue	• Invest in long-term, in person collaboration • Seek out non-conventional funding that enables sustained engagement • Align values and identify shared goal and purpose • Foster a team culture for open-mindedness and compromise
Deep Integration of knowledge domains	• Forged and strengthened partnerships with local stakeholders and institutions • Integrated quantitative and ethnographic approaches, as well as critical theory. • Assessed the potential harms of data collection and dissemination • Strove for accountability and reciprocity with communities at risk • Resisted the temptation to produce knowledge that might serve harmful ends	• Highlight the partiality and pluralism of knowledge by debating what constitutes "rigorous" or ethical data • Develop an inclusive group ethos that values listening, debate, and intellectual discomfort • Address ethical and political dimensions of research directly. • Use multiple communication strategies (e.g facilitation, small groups, shared meals)
Adapting Existing methodologies	• Adapted diverse methods—ethnography, remote sensing, causal inference, and simulation modeling—to approach complex problems from multiple angles. • Allowed intellectual friction to produce richer understandings (e.g., Pixelizing the Social). • Developed a data pedigree to integrate different partial indicators	• Leverage conceptual models and methodologies as "boundary objects" • Conduct collaborative, iterative analysis by continuously updating hypotheses and methods • Include researchers with lived or ethnographic experiences and methodological tools that enable systematic analysis • Consider "nonscientific" or nontraditional data sources (such as news media) to measure unconventional variables • Include junior to senior scholars to try new approaches and be prepared to fund multiple attempts if the first method fails
Generation of policy-relevant science	• Directly engaged policy makers, gathering their attention through high-profile and/or policy-relevant publications. • Sought policy windows to advocate for affected communities to media • Opened space for non-profits to cite our work to and request funding • Engaged the broader public by communicating in accessible formats and leveraging existing partnerships. • Sustained funding and publications over a long period through continued relevance	• Align societal needs with research objectives by seeking out stakeholder concerns and considering how results inform structural change. • Dialogue with on-the-ground regional collaborators by sharing research results and requesting feedback on tentative findings • Commit to communicating analysis and findings across multiple audiences to maximize the broader impacts of our work

ethnographic and remote sensing analysis to the extent that the line between these often-siloed epistemologies and methodologies blur. It also goes beyond previous approaches to "People and Pixels" human-environment problems, which proposed ways to bring together social science and remote sensing data to understand landscape change (National Research Council, 1998). This is because we iteratively use different methods–from econometrics to Agent Based Models to value chain analysis–to assess the same research question from different angles. Ultimately, this approach goes beyond "triangulation" –using mixed methods to shed light or converge on understanding a problem in two dimensions. Rather, a more apt metaphor would be slowly turning a kaleidoscope to reveal new dimensions and colors of the object and pattern that lies at the bottom–until those patterns become more predictable and answers to questions begin to repeat over time.

Third, we argue that convergence research and team science approaches addressing wicked problems require a concerted strategy of political accountability and public engagement. Public accountability entails being reflexive about the power relations and political stakes underpinning research efforts, rather than ignoring them, which runs the risk of reproducing inequality and causing harm. It also entails dialoging with grassroots actors and community members, who live with the daily reality of the wicked problem, about research design, risks, and findings. Disseminating and socializing research projects both with project participants and impacted communities is also central to politically accountable and publicly engaged research (see also Bennett et al., 2024; Davis, & Ramírez-Andreotta, 2021; Lemos et al., 2018). In many cases, collaborating with the press to translate and circulate research findings to popular audiences may also be appropriate to ensure the greatest benefit and impacts of science research are harnessed, especially given potentially high stakes and costs of doing the work. Ethical convergence science, especially about sensitive topics such as illicit activity, can take lessons from disciplines such as Critical Remote Sensing (Bennett et al., 2024), which suggests scientists consider the exposure, engagement, empowerment, and accessibility their data and findings may be supporting (or failing to support).

In pursuing convergence research through team science to study our wicked problem we have learned many lessons along the way. Throughout the article, we have discussed these key lessons learned, which are summarized in Table 1. Successful convergence research is not something that can be prescribed, but rather must emerge from within a collaborative team culture. While culture arguably cannot be designed, it can be cultivated; we have pointed to several intentional practices that have helped our team evolve and adapt to the demands of our research problem. It is our hope that these reflections can provide guidance and inspiration to other research teams grappling with wicked problems and seeking a convergence research approach.

CRediT authorship contribution statement

Jennifer A. Devine: Writing – review & editing, Writing – original draft, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization, Supervision, Visualization. **Nicholas R. Magliocca:** Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization, Resources. **Kendra McSweeney:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization, Project administration, Resources, Software, Supervision. **Beth Tellman:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization, Visualization. **Matthew Fagan:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization, Visualization. **Steven E. Sesnie:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Erik Nielsen:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of interests

The authors declare no competing interests.

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