Geography and Sustainability 4 (2023) 6–18

Contents lists available at ScienceDirect

Geography and Sustainability

journal homepage: www.elsevier.com/locate/geosus

Review Article

Broader applicability of the metacoupling framework than Tobler's first law of geography for global sustainability: A systematic review

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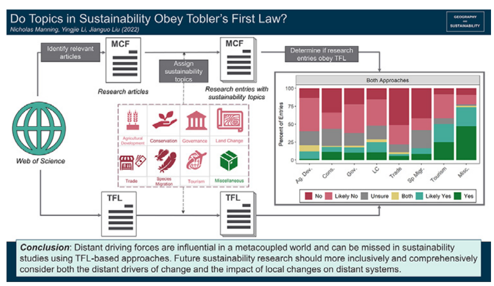
HIGHLIGHTS

- TFL and MCF have been increasingly applied to sustainability topics.
- We reviewed TFL & MCF literature to test if work in these topics obey TFL.
- TFL applied to only 13% of MCF literature.
- Species migration and trade research tended to disobey TFL.
- MCF offers a holistic approach to integrating nearby and distant systems.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 16 September 2022
Received in revised form 15 November 2022
Accepted 15 November 2022
Available online 19 November 2022

Keywords:
Telecoupling
Sustainability
Tobler's First Law of geography
Systematic review
Metacoupling

ABSTRACT

Complex sustainability issues in the Anthropocene, with rapid globalization and global environmental changes, are increasingly interlinked between not only nearby systems but also distant systems. Tobler's first law of geography (TFL) states "near things are more related than distant things". Evidence suggests that TFL is not infallible for sustainability issues. Recently, the integrated framework of metacoupling (MCF; human-nature interactions within as well as between adjacent and distant systems) has been applied to analyze the interactions between nearby and distant coupled human and natural systems simultaneously. However, previous work has been scattered and fragmented. It is crucial to understand the extent to which TFL and MCF apply across pressing issues in sustainability. Therefore, we reviewed and synthesized sustainability literature that used TFL and MCF across seven major topics: land change, species migration, tourism, trade, agricultural development, conservation, and governance. Results indicate MCF had a much broader applicability than TFL for these topics. The literature using MCF generally did not or likely did not obey TFL, especially in trade, governance, and agricultural development. In the TFL literature, most topics obeyed TFL, except for species migration and trade. The findings suggest the need to rethink and further test TFL's relevance to sustainability issues, and highlight the potential of MCF to address complex interactions between both adjacent and distant systems across the world for global sustainability.

1. Introduction

Geographical principles continue to play an important role in sustainability (Fu et al., 2022). However, sustainability issues are often highly intertwined and interlinked across space (Liu et al., 2015a). In the Anthropocene, an era with rapid globalization and global environmental changes, there is a great need to rethink the applicability and context of Tobler's first law of geography (TFL) in addressing sustainability issues under intensifying human-nature interactions, not only within a place and between adjacent places but also between distant places.

Waldo Tobler introduced his "first law of geography" in 1970 while modeling the population growth of Detroit, and stated "everything is related to everything else, but near things are more related than distant things" (Tobler, 1970). Some environmental processes can be described by TFL, for example, a slope on a surface will be more similar to areas

Abbreviations: MCF, Metacoupling Framework; TFL, Tobler's First Law of Geography; CHANS, Coupled Human and Natural Systems; WoS, Web of Science.

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https://doi.org/10.1016/j.geosus.2022.11.003

nearby, or soil samples taken near one another can be expected to be more similar than those taken from the other side of the field. TFL gained popularity during the 1980's as the quantitative Geographic Information System (GIS) and spatial analytical methods based on proximity grew in popularity (Foresman and Luscombe, 2017; Fotheringham and O'Kelly, 1989). TFL has also been the subject of numerous debates, the most detailed of which being the 2003 American Association of Geographers panel discussion surrounding, among other things, the meaning of "near" and "related" and what constitutes a "law" in geography (Sui, 2004). Tobler replied to this discussion, stating the main purpose of invoking this law was to simplify his Detroit growth model. He sought to make the most parsimonious model by only incorporating the crucial components to local growth. What Tobler actually reports is a measure of relation based on proximity, which is not a new concept. Moreover, laws across disciplines are also not new concepts, and, his article mainly gained traction because he invoked the term "law" to describe a general phenomenon of proximity and relatedness (Tobler, 2004). Some articles have extended TFL by offering slight adjustments, including accounting for spatially enabled economies (Foresman and Luscombe, 2017; Fotheringham and O'Kelly, 1989), relational space (Bergmann and O'Sullivan, 2018), multivariate analysis (Anselin and Li, 2020), and direction (Zhu et al., 2019). Despite these debates and caveats, TFL was integral to the development of spatial interpolation and spatial autocorrelation (Waters, 2017) and served as an important inspiration during the development of GIS (Goodchild, 2010; Sui, 2004).

The metacoupling framework (MCF) is another approach which focuses on relations across space. MCF simultaneously addresses human-nature interactions within, adjacent to, and distant from a given coupled human and natural system (Liu, 2017). The comprehensiveness and flexibility of MCF may prove it to be a worthy complement to TFL, as it can account for interactions between adjacent systems and distant systems (da Silva et al., 2021). This framework arose from multiple advancements in ways to examine the relationships between humans and the environment, and has been used to study many systems, such as the international soybean trade (da Silva et al., 2021) and the Arctic (Kapsar et al., 2022). MCF is typically applied by explicitly examining and instantiating the flows (e.g., movement of information, matter, energy, people, organisms) between systems. Liu et al. (2007) introduces coupled human and natural systems (CHANS) as a framework to describe the interactions between anthropogenic and natural systems (Liu et al., 2007). Past studies on CHANS have largely focused on one system. This idea was extended to the telecoupling framework, which stated two or multiple CHANS interact with one another over distances (Liu et al., 2013). In the telecoupling framework, each system is composed of agents, causes, and effects, and two or more systems are connected by flows of information, material, energy, people, capital, and organisms. Systems can be categorized as sending systems (the source of the flow), receiving systems (the destination of the flow), or spillover systems (systems that affect or are affected by the interactions between sending and receiving systems) (Liu et al., 2013). MCF is a holistic framework which can simultaneously describe interactions within a given system (intracoupling), between adjacent systems (pericoupling), and between distant systems (telecoupling) (Liu, 2017). Recent studies using MCF found that interactions between distant systems were more important than interactions between adjacent systems (Xu et al., 2020). However, evidence so far is scattered and fragmented. Therefore, there is a need to review and synthesize the context and applicability of TFL and MCF in addressing complex sustainability issues.

The typical definition of sustainability comes from the Brundtland Report (World Commission on Environment and Development, 1987) - "meeting the needs of the present without compromising the ability of future generations to meet their own needs", however, many other definitions exist (White, 2013). To limit our study to subject matters common across geography, sustainability, and metacoupling, we combined the major themes from the United Nations' Sustainable Development Goals (Messerli, 2018), the key elements for promoting sustainability (Fu et al., 2022), and the Telecoupling Toolbox (Tonini and Liu, 2017). Here, we investigate the extent to which TFL and MCF apply in agricultural development, conservation, governance, land change, species migration, tourism, and trade. The search terms for each of these categories can be found in Table 1.

Our study seeks to investigate the applicability of TFL and MCF across sustainability problems and the main contexts in which each is used. To address this, we conducted a systematic review of TFL and MCF literature, guided by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) standards (Page et al., 2021). We first used broad search terms to obtain relevant articles, screened the titles and abstracts, and separated the results from each approach (MCF or TFL) into their main sustainability topics. From here, we synthesized the most relevant literature on each sustainability topic. As a whole, we aim to examine and compare the roles of MCF and TFL in addressing several important issues in sustainability. Using MCF in tandem with TFL could be a powerful way to address sustainability issues involving geographically distant yet connected systems.

2. Materials and methods

This study sought to address how sustainability issues are viewed through two different approaches: TFL and MCF. We first iteratively narrowed our search terms until our desired terms for the two main approaches were found, then repeated this process for our topics. We marked if TFL applied and which approach was more appropriate for all relevant articles, and, finally, examined the major themes in the literature around each sustainability topic for MCF and TFL. The literature review and screening process are summarized in Fig. 1.

2.1. Identifying literature

A systematic review seeks to locate all relevant scientific information on a subject and synthesize this existing knowledge to create a novel finding (Siddaway et al., 2019). Our systematic review focused on exploring applications of TFL and MCF to pressing issues in sustainability. To accomplish this, we adapted and modified the PRISMA workflow to search Clarivate's Web of Science (WoS) database for relevant literature (Fig. 1). PRISMA is a standardized approach to conducting a systematic review, and includes the stages of "Identification", "Screening", and "Included" when identifying relevant research (Page et al., 2021). Because this study sought to compare MCF and TFL literature, we modified this workflow to be used on two sets of literature. We adapted this workflow to guide our systematic review, and conducted two separate screening stages instead of the single one outlined by PRISMA. We also included a step where we tested the extent to which the articles obeyed TFL and a final step in which we synthesized common themes across our results. These changes were chiefly made because we screened papers at each step, and because we were not combining quantitative results among studies, which is a common goal of systematic reviews, but rather examining common themes within different sustainability topics.

Our review process began by determining the search terms for each of the major approaches (MCF and TFL) used in articles published before March 2022. The terms selected simultaneously included the largest number of relevant articles and excluded irrelevant articles. This was achieved by searching several iterations of potentially relevant terms and conducting an initial title screening on the first fifty results of each search, as these comprised the first page of results in WoS.

Next, we defined which sustainability approaches we would compare throughout our study. Sustainability can be a somewhat vague and hard-to-define field (White, 2013). To bound our study, we combined the main themes from the "key elements for promoting sustainability" (Fu et al., 2022), the Telecoupling Toolbox (Tonini and Liu, 2017), and the United Nations' Sustainable Development Goals (Messerli, 2018) to seven prominent topics in sustainability. The seven main topics mentioned across these sources were land change, species

Table 1
Search terms for Web of Science.

Approaches	Search terms for each approach	Number of TFL articles (as of March 2022)	Number of MCF articles (as of March 2022)
MCF	(Metacoupl* OR Telecoupl* OR Meta-coupl* OR Tele-coupl*) NOT (*coupler)	NA	275
TFL	(Tobler NEAR "First Law") OR ("First Law" NEAR "Geography")	89	NA
Topics	**Search terms for each topic**	**Number of TFL articles (as of March 2022)**	**Number of MCF articles (as of March 2022)**
Land Change	("land cover" OR "land-cover" OR "land use" OR "land-use" OR "land change" OR "LCLUC" OR "LULC" OR deforest* OR (forest NEAR loss) OR urbanization OR (land NEAR fragment*) OR (land NEAR expansion) OR (land NEAR manag*) OR (land NEAR degradat*) OR (land NEAR acquisition))	17	138
Species Migration	(migration OR breeding OR wintering OR stopover OR (species NEAR migrat*)) NOT (labor OR "human migration")	2	20
Tourism	(ecotourism OR travel OR touris* OR flight OR traffic OR transpor*)	10	35
Trade	(trade OR import* OR export*) NOT (importan* OR tradeoff* OR trade-off*)	1	54
Agricultural Development	(agricultur* OR food)	3	106
Conservation	(conserv* OR biodivers* OR "biological diversity" OR "national park*" OR "nature reserve" OR "protected area" OR habitat*)	2	89
Governance	(governance OR legal OR "water rights" OR "indigenous rights" OR "land rights")	3	68

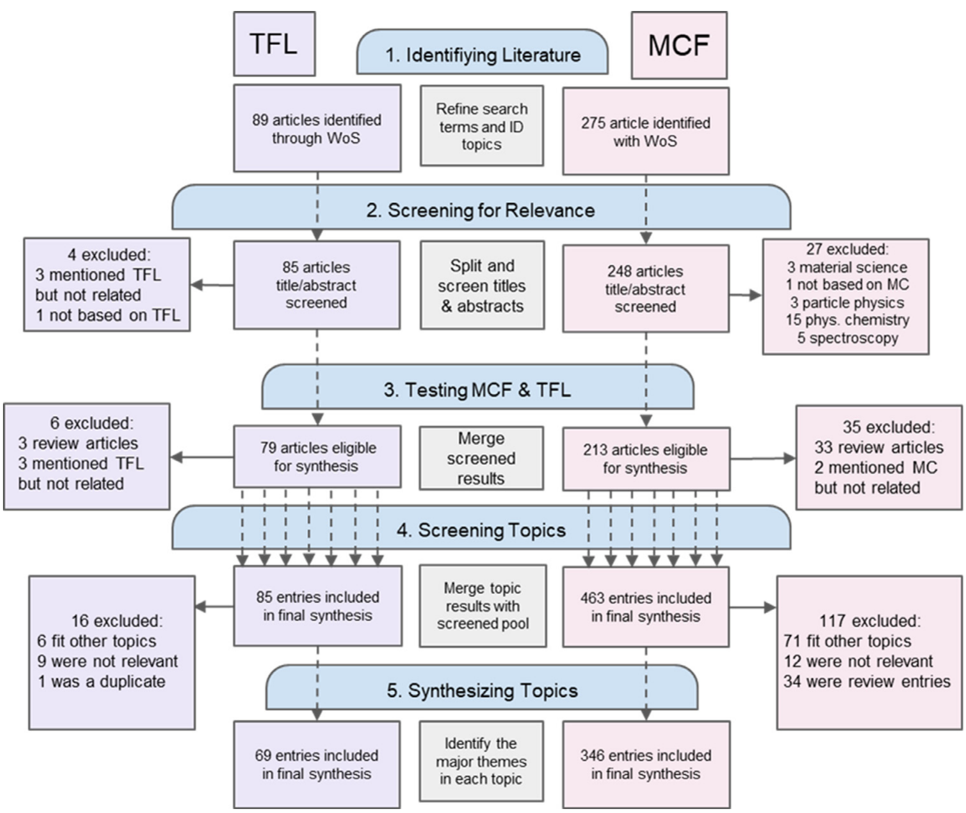

Fig. 1. The screening process from initial search to topic synthesis. We adapted the major stages of our review from the PRISMA workflow (Page et al., 2021), a comprehensive and methodical guideline to conducting systematic reviews.

migration, tourism, trade, agricultural development, conservation, and governance. We then filtered the initial TFL and MCF search results by performing another search with additional search terms composed of relevant phrases and keywords (e.g., "land cover" in our Land Change topic) related to each of the topics (Table 1). For example, Line 1 in the WoS search would include our main approach terms, and Line 2 would include the topic search terms, for a total of 14 searches (MCF and TFL per each of the seven topics).

2.2. Screening for relevance

After the seven topics were selected, we conducted a title and abstract screening on only the initial search results for MCF and TFL (Fig. 1). Doing this step first ensured each of our topic categories only contained articles relevant to MCF and TFL. We divided the search so two of the authors of this paper would individually review 40% of the articles each, and the remaining 20% would be reviewed by both to ensure we were consistent on our criteria for selection. For an article to be selected, it must (1) centrally focus discussion on or apply principles of MCF or TFL; (2) broadly fit the fields of Geography, Ecology, Environmental Science, or Sustainability; and (3) be available in English. After we selected the relevant articles, we met to discuss the shared 20% and conducted a full-text screening on any articles we disagreed on. Selection/exclusion screenings were conducted using R Version 4.1.1 in RStudio Version 1.4.1717 with the *revtools* package (Westgate, 2019).

2.3. Testing MCF and TFL

After the title/abstract screening, we examined the abstracts of each relevant article to determine if TFL applied here by checking: "When

Table 2
Criteria for testing if a certain entry obeyed TFL

Obeys TFL?	Criteria	Example Situations / Phrases	Example Reference	Quote from the Example Reference
No	States distant things are more related than nearby things	Distant forces drive, dominate, are more important, outpace nearby, or systems depend on distant	(Lira et al., 2022)	"Although mezcal has been marketed under an alternative production narrative that promotes sustainability, we see how consumption in distant areas has driven LULC changes in local production sites"
Likely No	Does not explicitly state whether or not it obeys TFL or use any indicator phrases, but the results seem to show it does not obey TFL	Distant forces are important to the results of the study, the study would be much different if the distant forces were excluded	(Tao et al., 2020)	"The results show that there is an essential decrease in both the number and density of winter rape patches under the opening global rapeseed market."
Unsure	It is not clear if the article obeys or does not obey TFL	The article may discuss both nearby and distant forces, but does not state which one is more important or it is unclear which one is more important from their results	(Fang et al., 2017)	"We also investigated the interactive coercion intensities between internal and external elements, and the mechanisms and patterns of local couplings and telecouplings in mega-urban agglomeration systems, which are affected by key internal and external control elements."
Both	There are separate areas that do or likely do obey TFL and do not or likely do not obey TFL	Relations range in intensity, e.g., a continental study where one country does obey and one does not	(Wang et al., 2022)	"Telecoupled interdependencies between Central Asian countries displayed complex directional relationships ranging from strong dependencies for some ES to no telecoupling relationships"
Likely Yes	Does not explicitly state that it does follow TFL or use any indicator phrases, but the results seem to show it obeys TFL	Nearby things / forces are very important to the results of the study	(Tonini and Liu, 2017)	"The number of pandas transported from the reserve to other zoos increased between 2000 and 2010, but more animals are transferred at shorter distances (within China) compared to those at farther foreign locations."
Yes	States nearby things are more related than distant things, connections within a system were strongest, or the focus system decreased in similarity with distance	Nearby forces drive / dominate, or are more important. The study i based on / derived from TFL	(Moreno-Fernández et al., 2021)	"... warfare and armed conflict primarily affects land systems locally, but can forge telecouplings"

considering geographic distance, does this article obey TFL?" More specifically, we marked each article as "obeying TFL" only if an article's findings support "near things being more related than far away things." We used the phrases "obeys TFL" and "TFL applies" interchangeably because if a phenomenon obeys TFL, we can also say this law applies to the phenomenon. If the extent to which TFL applied was unclear from the abstract, then a full-text screening was conducted before marking the article. Direct quotes and remarks which supported our decision on each entry are provided in the Supplementary Materials. While both TFL and MCF were created to deal with various types of distances (e.g., social and temporal) (Liu, 2017; Sui, 2004; Tobler, 2004), our study only focused on geographic distance.

To determine if an article obeyed TFL, we reviewed the article's abstract and/or full-text for relevant findings, especially those which stated the focal system's relations to other systems. Table 2 shows the six separate options for each article: "Yes", "Likely Yes", "Unsure", "Both", "Likely No", and "No". It also summarizes our criteria for each response. We considered an article to have "obeyed" TFL if the main findings showed that connections within a system were strongest, that a system was more similar within its boundaries and to its immediate neighbors than distant entities, or if the system decreased in similarity with distance. If it was not explicitly stated, but likely that the nearby things/forces outweighed the distant, the article was marked as "Likely Yes". If an article's major findings did not make it clear whether local or distant forces were more important, then the article was marked as "Unsure". If an article contained cases where one area did or likely did obey TFL and one area did not or likely did not obey TFL, the article was marked as "Both". A given article was marked as "Likely No" if it did not clearly state that distant things were more related, but the results would be very different if the influence of distant forces was omitted. An article likely did not obey TFL if the "distant things" seemed to be more related to each other than the "nearby things", but without clearly stating this. If an article did clearly state that the distant things were more related, then this article did not obey TFL and was marked "No". Sometimes, articles may have described distant things as the "driving force", "most important factor", or "dominant factor". These articles were marked as not obeying TFL because their main findings showed that distant forces were more important than nearby forces. For example, Lira et al. (2022) found global markets can drive local land-use changes by increasing demand (Lira et al., 2022). As market dynamics are external and geographically distant from the system of focus, this study was marked as not obeying TFL. The system boundaries were not always clear, so, throughout this study, we consider anything external, but not adjacent, to the system as distant, and internal or adjacent as nearby. Additionally, review articles and articles without clear quantitative or qualitative findings were excluded at this step.

2.4. Screening topics

We separated our results into seven topics and synthesized the major themes present in each topic to compare how MCF and TFL are applied across sustainability studies. To obtain our initial topic results, we determined the relevant search terms for each topic and conducted another WoS search by using AND operator to combine two lines of search terms. The first line included search terms for each approach (MCF or TFL), and the second line included new search terms, specific to each topic (Table 1). This essentially filtered our initial search results from each approach, and each topic search provided articles which were associated with both the major approach and a certain topic, resulting in 14 individual topic searches.

We then imported the topic search results into R, and joined them by DOI to the previously screened approach datasets to screen each of the topic results. This ensured each entry of each topic was relevant. Multiple topics could be assigned to one article, thus, when referring to the pool of literature with the topics assigned, we henceforth refer to each article as an "entry". For example, one article could be assigned to both the agricultural development and land change topics, so this single article would be counted as one entry in agricultural development and one entry in land change.

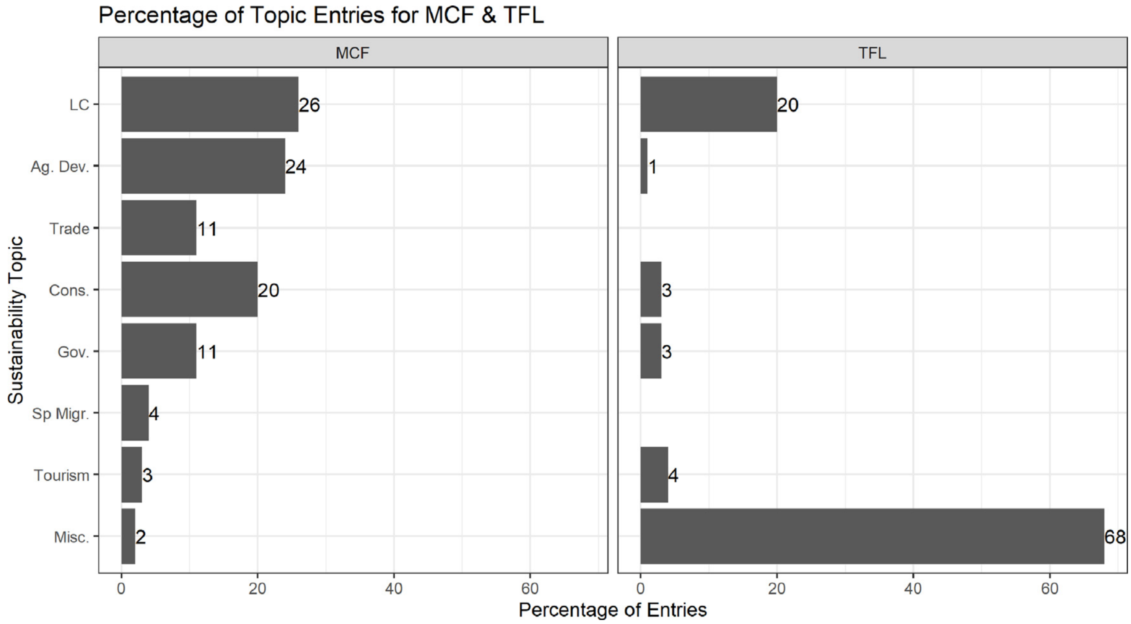

Fig. 2. The percentage of relevant non-review MCF and TFL entries by topic.

2.5. Synthesizing topics

After we had our screened topic results, we synthesized MCF and TFL approaches by manually identifying the most relevant articles from each topic and describing the common themes among them (Fig. 1). This step contained a final round of screening, where we examined if each article was a review, a duplicate, better fit to another topic, or irrelevant to our sustainability topics.

3. Results

3.1. Screening results

Our initial literature search yielded a total of 364 articles, 76% (275/364) of which were MCF-related studies and 24% (89/364) were TFL-related. Before we evaluated the final pool of literature across sustainability topics, we sequentially removed irrelevant articles and articles that were reviews (Fig. 1). In our initial screening, we removed 4 TFL articles and 27 MCF articles, yielding a total of 248 articles relevant to MCF and a total of 85 articles relevant to TFL. Of the irrelevant and excluded TFL articles, 3 articles mentioned TFL in the abstract but only in passing and 1 article mentioned TFL but was not relevant. The bulk of the irrelevant MCF articles came from similar terminology in light and chemical physics, with 3 articles from material science, 15 from physical chemistry, 3 from particle physics, 5 from spectroscopy, 2 which were duplicates, and 1 article was also identified as using metacoupling terminology (i.e., agents, flows, causes, etc.) but not being relevant to sustainability. During the next screening phase, we excluded 3 TFL review articles and 3 articles that were relevant but did not have any main qualitative or quantitative findings. In this phase, we excluded 35 more MCF articles: 33 review articles and 2 articles that mentioned MCF but were not related enough to include in our final synthesis. After this, there were 213 unique MCF articles and 79 unique TFL articles that were then assigned topics.

3.2. Sustainability topics under TFL and MCF

After we assigned the topics to each article, there were 342 MCF topic entries, and 85 TFL topic entries. Fig. 2 shows the percentages of entries in each major approach associated with each topic. Land Change (90 entries, 26%), Agricultural Development (81, 24%), and Conservation (69, 20%) had the most entries for MCF, while Miscellaneous (47, 68%), Land Change (14, 20%) and Tourism (3, 4%) had the most entries in TFL literature. Both MCF and TFL literature contain more entries published in recent years (2017–2021), with 2020 containing both the most TFL entries (13) and MCF entries (70). MCF has more entries overall and more recently published entries, as the year with the second highest entries published is 2021 (65), while the second highest year for TFL is 2017 (9).

Most entries located by the TFL search did not fall into a certain sustainability topic. Our MCF search had few entries that did not fit into a certain topic (6 entries, 2% of total MCF entries), which suggests MCF is a promising framework to approach sustainability issues. The miscellaneous TFL articles which presented new spatial analysis methods could be indirectly relevant to addressing sustainability issues by improving current techniques. However, these techniques may miss some important connections if they are solely based on TFL.

3.3. Applications of MCF and TFL across sustainability topics

Fig. 3 shows how the relevant entries obeyed or did not obey TFL. Sustainability entries found in MCF literature chiefly did not or likely did not obey TFL (211/346, 61%), while entries found in the TFL literature chiefly did or likely did obey TFL (59/69, 86%) (Fig. 3(b)). Specifically, in metacoupling literature, 84 entries did not obey TFL (25%), 127 entries likely did not obey TFL (37%), 15 entries did obey TFL (4%), 32 entries likely did obey TFL (9%), 15 entries included regions which did obey TFL and regions which did not obey TFL (4%), and there were 69 entries which were not clear if they did or did not obey TFL (20%) (Fig. 3(b)).

Within the TFL literature, 6 entries did not obey TFL (9%), 4 entries likely did not obey TFL (6%), 19 entries likely did obey TFL (28%), 40 entries did obey TFL (58%) and there were no entries which were unclear or included areas which did and did not obey TFL (Fig. 3(b)).

Studies across sustainability topics often did not obey TFL (Fig. 3(a)). Studies centered on trade, species migration, and conservation had the highest percentage of articles which did not obey TFL when considering both pools of literature and MCF separately. Other than miscellaneous entries, articles in the tourism topic did or likely did obey TFL were more frequent in both MCF and TFL literature.

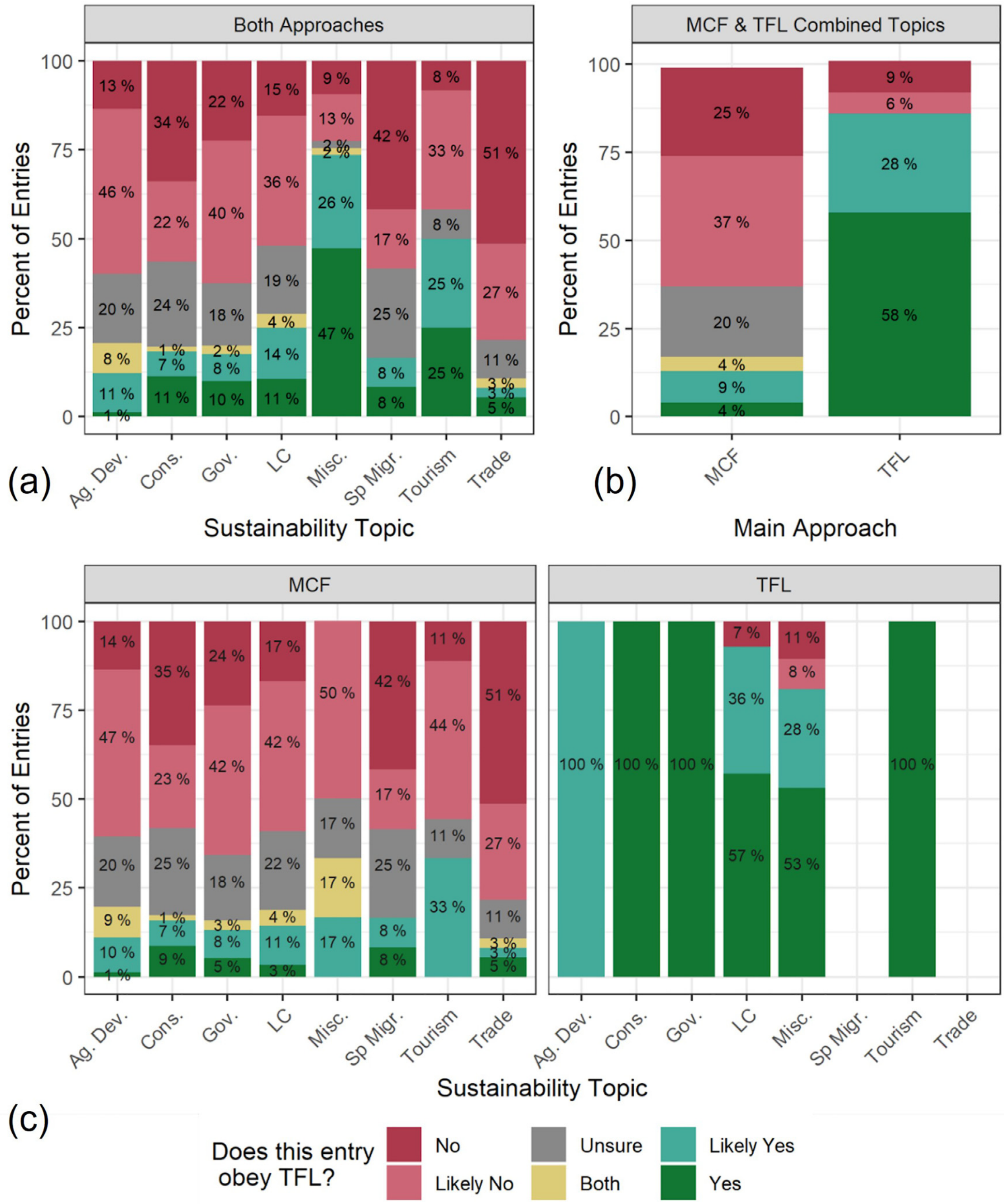

Fig. 3. The percentage of articles in each sustainability topic and if they obeyed TFL or not, with (a) both approaches taken together, (b) the sustainability topics considered together per each approach, and (c) separated by both approach and topic.

3.4. Sustainability topic synthesis

The MCF and TFL are both influential to the subjects of geography and sustainability, but in different ways. In this study, we focused on land change, tourism, agricultural development, governance, species migration, conservation, and trade, with an additional topic, miscellaneous, for any articles relevant to MCF, TFL, or sustainability, but which did not fit these topics.

In general, MCF tended to focus on describing the drivers of change (e.g., land change, tourism, agricultural development) or discussed new perspectives on problems (e.g., governance), whereas TFL focused on quantifying changes in land change, tourism, and agricultural development and building on existing models in governance. Compared to TFL, MCF studies focused on more geographically expansive areas, often at the global scale (Chung et al., 2020) or by including international influences (Chung et al., 2018b; Liu et al., 2015a; Yao et al., 2020). We also found many TFL articles which did not fit within our topics, which could mean TFL studies are wide-ranging. But, this could also simply suggest MCF articles more often explicitly use metacoupling vocabulary, where a study could be based on or obey TFL but not explicitly state this in the title/abstract.

3.4.1. Agricultural development

We define agricultural development as any study which focuses on agriculture or food. TFL is not commonly cited as a factor in agricultural development, perhaps because these studies have often focused on either the distant forces driving development or the global impacts of local changes. The 1 entry (1%) we found summarized the impact of von Thünen's work on land change and suggests an amendment to TFL which states that near things are more related than distant things as a consequence of accessibility (Walker, 2022).

MCF has played an increasingly important role in describing how distant demand can impact local agricultural systems (Tao et al., 2020), how changes within and across adjacent systems can be measured (da Silva et al., 2017), and how the changes within a local agricultural system can impact other distant systems (Martínez-Valderrama et al., 2021). MCF studies tended to focus on the agricultural development of a certain focal region per study, and how that area impacted other regions or systems. MCF results also focused on the multi-scale distant and interregional forces influencing agriculture in Africa (Burra et al., 2021; Hauer and Nielsen, 2020), California (Marston and Konar, 2017), and Israel (Fridman and Kissinger, 2019). Another common theme between MCF results in this topic was the focus on locusts and their connection to local livestock and global commodity markets (Cease et al., 2015; Gall et al., 2019; Wyckhuys et al., 2018).

3.4.2. Species migration

Among the 12 identified articles on species migration, none is related to TFL, but all to MCF. This is mainly due to the fact that species migration usually takes place across large transboundary regions and over a long distance. For instance, millions of animals take long-distance migration around the world, and some travel more than 50,000 miles (Hulina et al., 2017). Since biodiversity can help maintain and deliver important ecosystem services, migratory species therefore play a critical role in providing ecosystem goods and services (e.g., pest control, recreational and cultural services) across regions (López-Hoffman et al., 2017a; Schröter et al., 2018). For example, birds migrating between Germany and Africa provide pest control to German agricultural areas (Kleemann et al., 2020). Moreover, migratory monarch butterflies are subsidized by overwintering habitat in Mexico, while providing tremendous cultural benefits to the U.S. and Canada.

Apparently, TFL is not suitable for approaching this topic, while conceptualizing species migration as metacouplings can essentially help investigate how the migration connects and impacts the sending, receiving, and spillover systems across distances (Hulina et al., 2017; Liu et al., 2014). Inspired by the metacoupling framework, the spatial subsidy approach was proposed to specifically measure the degree to which the provision of benefits by a species in one location is subsidized by ecological conditions and processes supporting the species in other locations (López-Hoffman et al., 2017b).

3.4.3. Conservation

Conservation studies in this review generally include research on preventing the loss of Earth's biological diversity and protection of natural resources. There are two conservation entries related to TFL, one of which used distance decay to develop a spectral distance proxy to characterize ecosystem beta-diversity (Rocchini, 2007) and the other found proximity to national parks can help halt land use change (Olaniyi et al., 2020). Among the 89 conservation entries, 30 specifically adopted MCF and covered a variety of themes. For example, research found that migratory species conservation needs to take inclusive and global approaches and implement efforts in multiple metacoupled systems (such as breeding, wintering, and stopover sites) (Hulina et al., 2017; López-Hoffman et al., 2017b). In addition, distant consumptions through international trade were revealed to cause unexpected habitat losses (Green et al., 2019; Lenzen et al., 2012) and generate negative impact on sustainable fisheries (Carlson et al., 2020, 2019). To tackle biodiversity loss and ecosystem degradations, both international and domestic conservation measures have been taken, such as international conservation financing (Qin et al., 2022) and area-based conservation (e.g., nature reserve and national parks; Liu et al., 2015a). Although with good intentions, some place-based conservation efforts could generate negative spillover effects and compromise sustainability in distant places (Liu, 2014).

3.4.4. Governance

Our governance topic includes studies on water, land, and indigenous rights, among other legal frameworks. Here, we found 2 TFL governance entries (3%) and 38 MCF entries (11%). TFL entries typically addressed governance issues, such as mismatches in spatial boundaries (Agyemang et al., 2017), by developing or building models. Governance in MCF entries ranged from defining new governance issues to addressing governance problems conceptually and quantitatively across a wide range of subjects and scales. While MCF results tend to be more broadly applicable (e.g., defining what governance means in MCF systems (Newig et al., 2019)), there are also entries which address specific local governance issues (e.g., using remote sensing to define eco-certification impacts; da Silva et al., 2019). MCF entries differed from TFL here in that they explored ideas and applied MCF to more emerging fields, such as environmental justice (Boillat et al., 2020). Similar among both approaches is the use of their core conceptual frameworks to develop new methods and concepts.

3.4.5. Land change

Land change science is an interdisciplinary field which synthesizes land-cover land-use changes and their causes to address questions of global environmental change and sustainability (Turner et al., 2007). Land change entries were are the second-most common in TFL (14, 20%) and the most common in MCF (90, 26%) results. We found TFL entries chiefly developed new remote sensing indices (Chen et al., 2016; Olaniyi et al., 2020) or machine learning methods (Cui et al., 2021) to quantify the extent of land change. MCF entries included the international soybean trade and indirect land-use change across scales. Several MCF articles found distant countries' demand for soybeans drives production and agricultural expansion in other countries (Green et al., 2019; Schaffer-Smith et al., 2018) and that pericoupled (i.e., adjacent) systems are also impacted when distant forces drive change (da Silva et al., 2021; Dou et al., 2018). Soybean trade was much larger among distant countries than among adjacent countries (Schaffer-Smith et al., 2018). MCF entries also showed local land-use decisions have telecoupled implications (Newman et al., 2021), and the policies of distant countries can drive local change (Rulli et al., 2019).

We found MCF tended to use agent-based modeling (ABM) (Dou et al., 2020; Yang et al., 2022), while TFL tended towards cellular automata (CA) (Zhao and Murayama, 2007). While distant influences may be captured as an emergent property in a CA model (Batty, 1998) and in ABM models, MCF explicitly accounts for both nearby and distant influences (Liu et al., 2015b), and future CA models should incorporate telecoupled impacts on land change (Kim et al., 2019).

Studies using MCF sought the causes of direct and indirect land change, where TFL may mention the drivers, but instead developed methods to measure the impact of the drivers, not necessarily their origin. For example, following TFL, an entry stated urban expansion and mining drove land use/cover changes, while an MCF approach might extend this to assess the distant drivers of urban expansion and mining, as mining often has metacoupled impacts external to a focal system (Yuan et al., 2022).

3.4.6. Tourism

Among the studies on how tourism may impact the world (Liu et al., 2015b), 3 TFL entries (4%) and 9 (3%) MCF entries focused on tourism. Compared to TFL studies, which tended to center on one focal site, MCF studies focused on more geographically expansive areas, often at the global scale (Chung et al., 2020) or by including international influences (Chung et al., 2018b; Liu et al., 2015a; Yao et al., 2020). Some MCF studies also used tourism as a basis to explain other factors, such as ecosystem services (Chung et al., 2018b; Yao et al., 2020) or biodiversity

(Chung et al., 2018a), where in TFL studies, tourism itself was either the primary subject of the investigation (Joo et al., 2017; F. Xu et al., 2020) or the driver of land change (Olaniyi et al., 2020).

3.4.7. Trade

There were 37 identified studies on trade, none of which aligned with TFL, but many with MCF. Similar to species migration, trade is more commonly framed among transboundary regions and countries. The trade of agricultural products, such as soybeans (da Silva et al., 2017), natural rubber (Laroche et al., 2022), and wood products (Parish et al., 2018), are the most studied in the literature. The production and consumption of these agricultural products are usually linked to land use change (Fuller et al., 2019), deforestation (Norder et al., 2017), biodiversity (Green et al., 2019; Schwarzmueller and Kastner, 2022), energy (Kalt et al., 2021), water use (Du et al., 2022), and other environmental footprints (Barbieri et al., 2022; Galvan-Miyoshi et al., 2022). Research also revealed that some traded food products (e.g., red meat and processed meat) can lead to human health concerns (Chung et al., 2021; Chung and Liu, 2019). Recently, there is a growing interest in addressing the distant impacts of trade by promoting eco-certified products, e.g., certified coffee and forestry products (Klapper and Schröter, 2021; da Silva et al., 2019). In addition to agricultural products, seafood (Bronnmann et al., 2020; Carlson et al., 2021), wild species (Klapper and Schröter, 2021), and animal-derived products (Matlhola and Chen, 2020) also drew much attention in the trade literature, with a concern that animal-derived products impair biodiversity. Trade analysis largely relies on statistical data of trade records, while models such as gravity models (Kabir et al., 2017; Kepaptsoglou et al., 2010) and Telecoupled Agent-Based Models (TeleABM) (Dou et al., 2020) have been developed to simulate and understand the dynamics of trade under different socio-environmental scenarios.

3.4.8. Miscellaneous

During the topic assignment process, if a certain article did not fit into any specific sustainability topic but was still marked as a relevant entry, it was assigned to the miscellaneous topic. This category had, by far, the most TFL entries (47 entries, 68%), and significantly less MCF entries (6 entries, 2%).

Most of the relevant TFL articles do not seem to fit into the outlined sustainability topics. It is common for “near” and “distant” to be framed as geographic space in TFL, but several articles offered different perspectives on TFL, including redefining regions on their relational similarities rather than their distance (Bergmann and O’Sullivan, 2018), stressing the importance of direction in distance (Zhu et al., 2019), comparing the similarities and spatial dependencies of multiple variables (Anselin and Li, 2020), and offering a “second law of geography” based on spatially-enabled economies in the Internet of Things (Foresman and Luscombe, 2017). Specific applications of spatial analysis to address TFL include analyzing how physical entities disrupt the similarities of “near” things (Mitchell and Lee, 2014) and the quantification of Wikipedia links between nearby entities (Hecht and Moxley, 2009). Several articles introduced new TFL-based methods in environmental science, including merging spatially and temporally near radar and rain gauge values to estimate precipitation (Tang et al., 2018), decision trees (Pu et al., 2007) and pattern mining algorithms for spatial associations (Yao et al., 2017). Two subjects are commonly discussed in TFL analyses which did not fit any of our sustainability topics: housing (Sairi et al., 2020) and air pollution (Li, 2021).

Most MCF studies were relevant to the sustainability topics we included in our study. These included one potential governance article promoting the telecoupling framework in fisheries management (Carlson et al., 2017), one tourism article discussing attachments to place (Gurney et al., 2017), one agriculture article on coffee production (Adane and Bewket, 2021) and two trade articles.

4. Discussion

MCF was more widely applicable than TFL across the seven sustainability topics included in this study. A strength of MCF is its ability to incorporate both adjacent and distant factors (Liu, 2017) with a particular interest in examining the often-ignored interactions among distant systems (i.e., telecouplings). Generally, the broad scope and comprehensive nature of MCF allowed us to detect entries that disobeyed TFL.

There were several reasons why TFL was not applicable in studies which used MCF. TFL was developed as a guiding principle in geographic modeling, one that may not be as relevant when dissecting certain sustainability topics, which can have important implications. For example, tourism, especially distant tourism, generates large footprints, such as carbon emissions (Liu et al., 2015a). Species migration and trade are lacking any research on TFL, as we did not find any articles with our keywords. These topics tend to involve geographically distant systems, and thus are likely to use methods unconstrained by the concepts of distance decay. In trade, costs for rail transportation, aviation fuel, roads, etc. have dropped dramatically or can be subsidized by the government, which makes cost no longer a major constraint of long-distance shipping, thereby facilitating the connection between distant places. In species migration, migratory species can travel with their food, unconstraining them from local relations and food webs. Moreover, MCF was developed to specifically and actively include human influence and interaction with natural systems, while TFL observes and explains physical phenomena and patterns. Including human influence is an important reason why TFL may not be applicable in studies which focus on metacoupled systems and geographically distant yet highly related systems.

The influence of anthropogenic forces in coupled human-natural systems is important to note, as they can shape natural environments and interrupt natural processes. The law of conservation of energy states that energy in an isolated system cannot be created or destroyed, only transformed or transferred. However, the relevance of the thermodynamic interpretation of entropy is questionable in landscape ecology, especially when focusing on complex systems (Vranken et al., 2014). The connections between complex socio-ecological systems show these are not isolated systems, and that distant systems can drive change in local systems through the addition of human influences, and vice versa - local changes can produce distant impacts. In systems ecology, systems are typically viewed as “open” as they often have connections outside of their respective boundaries (Kitchling, 1983). Human intervention can be considered a mechanism by which energy is transformed and transferred in this “open system.” Macrosystems biology, for example, shows the importance of scale and human interaction in complex systems, and it has been shown that the increased frequency of distant interactions can outweigh the importance of proximity for human impact on natural systems. Downstream accumulation of nutrients and increased international trade are two examples which highlight distant relations being stronger than nearby in human-natural systems (Tromboni et al., 2021). The interplay between existing natural laws, such as a downstream environment being linked to upstream riparian conditions (the downstream “shadow” effect (Fejió-Lima et al., 2018)), and the addition of energy from human intervention in the system can lead to impacts which could be misdescribed, misattributed, or unexplainable if viewed through TFL.

Our approach to comparing TFL and MCF across current sustainability literature came with several limitations. We only included publications in English, so we may have missed important contributions written in other languages. Some sustainability-related topics, such as payments for ecosystem services (Yang et al., 2013) and environmental impacts of household dynamics (Bradbury et al., 2014) and lifestyles such as divorce (Yu and Liu, 2007), were not explicitly included. Our classification involved some degree of subjectivity, as entries usually did not explicitly declare if the studied subject obeyed or disobeyed TFL and it was sometimes difficult to identify the boundaries for the systems in each entry. For example, TFL may have applied within a certain system boundary. However, a neighboring system, maybe a bordering country

Table 3
The major themes in each sustainability topic

Topic	Approach	# Entries (%)	Main Themes
Agricultural Development	TFL	1 (1%)	Explore theory and amend TFL (Walker, 2022)
	MCF	81 (**24%**)	Agricultural development of certain regions (Brazil (da Silva et al., 2017), Mediterranean (García-Martín et al., 2021), Africa (Burra et al., 2021), California (Marston and Konar, 2017)) and their impact on distant places; Locusts connections to local livestock and global commodity market (Cease et al., 2015; Wyckhuys et al., 2018)
Species Migration	TFL	0 (0%)	NA
	MCF	12 (4%)	Migratory species play a critical role in providing ecosystem goods and services (e.g., pest control, recreational and cultural services) across regions (López-Hoffman et al., 2017a; Schröter et al., 2018) Conceptualizing species migration as metacouplings can essentially help investigate how the migration connects and impact the sending, receiving, and spillover systems (Hulina et al., 2017) The spatial subsidy approach was proposed to specifically measure the degree to which the provision of benefits by a species in one location is subsidized by ecological conditions and processes supporting the species in other locations (López-Hoffman et al., 2017b)
Conservation	TFL	2 (3%)	Distance decay can be used to develop a spectral distance proxy to characterize ecosystem beta-diversity (Rocchini, 2007) Proximity to the national park helps halt land use change (Olaniyi et al., 2020)
	MCF	69 (**20%**)	Remote consumption can lead to unexpected habitat losses for the iconic species (Green et al., 2019) Migratory species can provide ecosystem services across distances (Semmens et al., 2018), and the conservation efforts need to apply the telecoupling framework to understand and manage both adjacent and distant systems such as breeding, wintering, and stopover sites. Spatial subsidy was proposed to operationalize the framework by identifying sending and receiving areas, and by indicating the degree to which locations are telecoupled to other locations (Kleemann et al., 2020; López-Hoffman et al., 2017b). (Forest) Conservation efforts in one place might offset sustainability in remote places (Liu, 2014). Cross-boundary tourism and wildlife translocations also impact the trade-offs in between achieving sustainable development goals (Zhao et al., 2020) International conservation interest affected by socio-ecological links between donating and receiving regions (Qin et al., 2022) Sustainable fisheries management needs to consider telecoupled factors, such as trade and diseases, fishing catches in adjacent and distant exclusive economic zones (EEZs) (Carlson et al., 2020, 2019) Nature-based tourism and biodiversity conservation in protected areas can achieve win-win outcomes (Chung et al., 2018b)
Governance	TFL	2 (3%)	Develop new models to track regional change in China (Zhai et al., 2019) and Ghana (Agyemang et al., 2017)
	MCF	38 (11%)	Establishing general guidelines for governing metacoupled systems (Eakin et al., 2017; Newig et al., 2019) Governing specific metacoupled systems (great lakes fisheries (Eakin et al., 2017) and land systems (Oberlack et al., 2018)) Eco-certification (da Silva et al., 2021) Environmental justice (Boillat et al., 2020)
Land Change	TFL	14 (**20%**)	Cellular automata models (Zhao and Murayama, 2007) Develop remote sensing indices (Chen et al., 2016) Develop machine learning methods (Cui et al., 2021)
	MCF	90 (**26%**)	Agent-based models (Dou et al., 2020; Yang et al., 2022) Distant demand drives soybean production and expansion in Brazil (Green et al., 2019; Schaffer-Smith et al., 2018) Local land-use decisions and distant decisions impact one another (Newman et al., 2021; Rulli et al., 2019)

(*continued on next page*)

Table 3 (*continued*)

Topic	Approach	# Entries (%)	Main Themes
Tourism 	TFL	3 (4%)	Relation to a destination decreases with distance (Olaniyi et al., 2020; F. Xu et al., 2020) Different areas correspond to different types of tourism (Joo et al., 2017)
	MCF	9 (3%)	Distant tourists impact water sustainability (Chung et al., 2020; Yao et al., 2020) Nature-based tourism can support biodiversity (Chung et al., 2018b) Tourism can both link sites to spillover systems and act as a spillover system (Liu et al., 2015a)
Trade 	TFL	0 (0%)	NA
	MCF	37 (11%)	Trade of agricultural products, such as soybean (da Silva et al., 2017), natural rubber (Laroche et al., 2022), wood products (Parish et al., 2018), is a main focus in the literature. Seafood is also increasingly globally traded (Bronnmann et al., 2020; Carlson et al., 2021). Trade of wild species (Klapper and Schröter, 2021), and animal-derived products (Matlhola and Chen, 2020) is threatening biodiversity worldwide.
Miscellaneous 	TFL	47 (**68%**)	Amending / extending TFL (Anselin and Li, 2020; Bergmann and O'Sullivan, 2018; Foresman and Luscombe, 2017; Zhu et al., 2019) Spatial analysis (Hecht and Moxley, 2009; Mitchell and Lee, 2014) New methods in environmental science (He et al., 2013; Pu et al., 2007; Tang et al., 2018) TFL subjects outside of our sustainability topics (housing (Sairi et al., 2020) and air pollution (Li, 2021))
	MCF	6 (2%)	Entries which were not picked up by our search terms but could have fit in other topics (governance (Carlson et al., 2017), tourism (Gurney et al., 2017), agriculture (Adane and Bewket, 2021), trade (Xiong et al., 2018))

or area, might not follow TFL. This means that the system "near" the focal system is not as related, but TFL still applied within the focal system. Moreover, if the same distant forces were driving changes across a focus system and a "nearby" neighboring system, then these two nearby systems are related as they are driven by the same distant forces.

Based on our search criteria, we initially found a larger number of MCF articles than TFL articles. MCF articles tended to include multiple aspects of sustainability, thus, our final pool of entries also had many more MCF entries than TFL entries, and few entries that used both MCF and TFL. In addition, more studies here adopted MCF than TFL even though the initial publication of MCF was several decades more recent than that of TFL. MCF is a new research frontier with wide applicability, so many authors have been attempting to apply, quantify, and expand on this framework. TFL entries may not explicitly state that their approach was based on TFL, as this law may be implied in the methods they use. This could be another reason why there were so many miscellaneous TFL articles and so few miscellaneous MCF articles.

The TFL percentages and combined percentages presented in Fig. 3 should be taken with caution . There were many more MCF entries than TFL entries in several subtopics (e.g., agricultural development, conservation, and governance; Table 3), and this likely led MCF to have a larger impact on the total merged percentages than TFL. Essentially, when considering the total number of entries, MCF was more heavily weighted when they were merged to produce the combined results (Fig. 3(a)).

It is important to note that we are not stating TFL is completely invalid; instead, we provide MCF as a tool to handle subjects where distant things are more related, and thus may not be considered using TFL. There are several instances we have found where nearby things were more related, and thus using TFL might, depending on the study objectives, be appropriate for these studies. However, in situations where nearby things are more related, MCF is still useful and perhaps more appropriate when human-nature interactions are important. Moreover, MCF provides a way to systematically address influences external to a system and the effects of changes in a system on distant places, although the concept of external influences themselves is not new. In fact, Tobler's second law states, "the phenomenon external to an area of interest affects what goes on in the inside" (Tobler, 1999). However, MCF provides a method for clearly specifying focal systems, adjacent systems, distant systems, spillover systems, agents, causes, effects, flows, and their interactions and feedbacks. Furthermore, it provides an integrated framework for inherently integrating humans and nature, systematically assessing these phenomena, and determining the extent to which they affect what goes on between adjacent/distant systems and within a focal system.

5. Conclusions and future perspectives

The growing convergence between sustainability issues and the field of geography creates a need to re-examine Tobler's first law of geography and how it applies across domains of sustainability. Through our multi-stage literature review and synthesis, we found over 2.5 times as many MCF articles than TFL articles. Most MCF articles focused on conservation, land change, and agricultural development, while TFL articles mostly fit into the miscellaneous topic or were associated with land change or tourism. Broadly speaking, MCF articles focused on determining the drivers of change and focused on indirect or distant influences. TFL articles tended to be more methodological, and mainly measured the extent of change, developed new spatial analysis methods, or introduced amendments and caveats to TFL. In terms of general literature trends, we found most MCF articles did not or likely did not obey TFL, while the vast majority of TFL articles did or likely did obey TFL.

Although interactions between geographically nearby systems can follow TFL, across several topics we found the distant driving forces on a system, which are influential in an interconnected world, are generally missed by solely basing a study on TFL. In these topics, distant things were responsible for the main results of a majority of the entries. Our findings suggest that sustainability research must consider distant systems and telecouplings, as they often play an important and unignorable role in the research. Framing research in these topics using TFL may not be an accurate representation of the real system being studied, and could impact the overall findings. In general, we found most studies across the examined sustainability topics involve systems with complicated external phenomena which cannot be addressed by using TFL alone.

Human intervention could be considered as a major mechanism that transforms or transfers energy across complex interconnected systems and facilitates the connection between distant systems, as human impacts on natural systems have generally reduced the importance of proximity (Tromboni et al., 2021). This trend is especially true with international trade, a topic that is inherently distant. While human intervention is one major mechanism here, it is important to note that natural phenomena, such as animal migration, can offer other methods for energy to be transformed and transferred without human interaction. Even studies which focus on one area (e.g., production of artisanal products in Oaxaca, Mexico; Lira et al., 2022) or species (e.g., migration of Mexican free-tailed bats; López-Hoffman et al., 2017b) show the influence of distant forces should not be ignored.

Across our literature review, we found several topics which generally disobeyed TFL. We are not, however, suggesting TFL is always false and never should be considered. There are still physical processes dependent on proximity. If TFL were completely disregarded, the way to describe relations between nearby areas would be “excessively chaotic” (Tobler, 2004), in that spatial autocorrelation would not exist. Instead, we appeal that sustainability studies should examine the distant drivers of change more inclusively and comprehensively, and the metacoupling framework offers a systematic approach to more effectively understand these complex dynamics.

In future work, it is necessary to pay more attention to the complementary roles of MCF and TFL. Based on existing literature we reviewed, spatial analysis research can still use TFL as a guiding principle, but should be cautious about the distant influences they may be omitting. MCF and TFL can be used in tandem across sustainability topics. MCF can be used to explicitly compare the impacts from distant systems versus those from adjacent systems as well as interactions between focal, distant and adjacent systems, thereby helping test under what context TFL holds true or not. Sustainability studies can use TFL to guide spatial analysis when nearby systems are related, and should adopt MCF to simultaneously address nearby and distant factors. In a metacoupled world, sustainability studies do not need to abandon TFL, but must recognize the importance of distant influences.

Declaration of Competing Interests

The authors declare that there are no known competing financial interests or personal relationships that influenced the work reported in this paper.

Acknowledgements

We are grateful to Falk Huettmann, Shurong Zhang, and an anonymous reviewer for their very helpful comments on the manuscript. We thank the National Science Foundation (Grants No.1924111, 2033507 and 2118329) and Michigan AgBioResearch for financial support.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.geosus.2022.11.003.

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