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The value of agent-based modelling for assessing tourism–environment interactions in the Anthropocene

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Tourism is one of the prime manifestations of the 'great acceleration of humankind' since the Anthropocene started around 1950. The almost 50-fold increase in international tourism arrivals has substantial implications for environmental sustainability, but these have not yet been fully explored. This paper argues that a full exploration requires the study of tourism as a complex socio-ecological system. Such approach integrates environmental processes and stakeholder behaviour and puts feedbacks in the spotlight. Systemic insights can inform strategies to address tourism's problematic environmental performance. The paper finds that systems approaches in tourism research are rare and identifies a number of challenges: the large number of stakeholders involved; the heterogeneity of stakeholders; and the lack of transdisciplinarity in tourism research. The paper then argues that agent-based modelling can help address some of these challenges. Agent-based modelling allows to run simplified tourism systems with heterogeneous stakeholders and explore their behaviour, thus acting as living hypotheses. They do this by: (1) representing tourism's dynamics in a systemic, intuitive and individual-based way; (2) combining theories from different domains; (3) unpacking the link between stakeholder behaviours and emergent tourism system patterns; and (4) connecting researchers and stakeholders. Agent-based models allow representation of heterogeneous agents driven by plausible needs, who perceive local context and interact socially. Companion modelling is identified as a promising tool for more effective stakeholder inclusion.

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Introduction

Tourism is one of the largest industries in the world, generating 10% of global GDP and accounting for 1 in 11 jobs, 7% of all exports and 30% of services exports in 2015 [1]. The growth of international tourism, from 25 million international arrivals in 1950 to 1.2 billion in 2015 [2], is one of the twelve socioeconomic trends included by Steffen *et al.* [3••,4] in their 'Great Acceleration' in human activity since 1950. As their work illustrates, the phenomenal growth in the human enterprise since 1950 (as also represented by dramatic increases in factors, such as population, urbanisation, income, transportation and telecommunications) corresponds closely with substantial shifts in the structure and functioning of Earth's ecosystems. According to these and other authors [e.g., 5], the beginning of this Great Acceleration also marks the beginning of a new geological epoch, the Anthropocene, an era driven by human influence. Tourism scholars have

recently started to explore the role of tourism in the Anthropocene [6].

Tourism benefited disproportionately from the large increases in disposable income in the western world post-World War II. Rapid advances in transportation and communication technologies increased the extent of travel and lowered prices, making short-haul and long-haul travel affordable for a large share of the population in developed countries. More recently, the desire and ability to travel has spread throughout much of the world; the number of international tourist arrivals is projected to double between 2010 and 2030, with arrivals in emerging economies growing at double the rate of those in advanced economy destinations [1].

In the first decades of post-WWII growth, tourism was often depicted as a benign industry with substantial social and economic benefits and limited environmental impacts. In more recent years, however, the negative social and environmental effects of tourism have been clearly exposed (see [7] for an overview), for example in the Journal of Sustainable Tourism. Most work in this field consists of qualitative studies in local case study areas as controlled experiments are difficult to execute in the context of tourism; until a decade ago only few studies had addressed the global scale of tourism-environment interactions. Gössling [8] was arguably the first to quantify tourism's global environmental impacts. More recently, Gössling and Peeters [9•] provided an accounting of tourism's total global resource utilisation, incorporating tourism-related fossil fuel consumption and associated CO_2 emissions, as well as fresh water, land and food use (c. 16 700 PJ of energy, 138 km^3 of freshwater, 62 000 km^2 of land and 39.4 Mt of food, causing emissions of 1.12 Gt CO_2). Further, their analyses indicated that resource use associated with tourism may double for water and triple for land use in the period 2010–2050.

In addition to contributing to the Great Acceleration and its environmental impacts, tourism is also affected by them. In the context of climate change, Scott *et al.* [10] discern four categories of potential impacts on tourism: direct (e.g., changing weather patterns and sea level rise), indirect environmental (e.g., biodiversity distribution and water availability), indirect societal (e.g., political stability and economic growth) and mitigation-policy-related (e.g., taxation of fuel, which affects travel costs). Substantial changes in the climatic attractiveness of tourism destinations have been reported for both summer tourism (see e.g., [11] for Australia) and winter sports. Snow reliability has already changed for winter sports destinations such as the European Alps [12] and further change is anticipated (see e.g., [13]).

The ultimate effects of global environmental change on tourism demand patterns will depend on perceptions, institutional flexibility and other societal factors that are currently poorly understood [14]. This knowledge gap is illustrative of a wider issue. A basic understanding of some of the main relationships between tourism and the global environment has emerged, but insights pertaining to the various issues have not been connected. In addition, feedbacks are under-represented. Studies of changes in tourism resources, such as climate, typically provide little insight into the stakeholder adaptation that such physical changes entail. In their turn, studies of stakeholder adaptation typically include rudimentary representations of environmental change at best. In short: an integrative, systemic approach is lacking. The key issues may be clear, but not the trade-offs between them nor the effects of changes in policy and behaviour (e.g., changes in destination choice, installation of snow-making equipment). Knowledge of these feedbacks is crucial for effective interventions to foster sustainability. Determining 'institutional, economic, and behavioural changes to enable effective steps towards global sustainability' is one of the grand challenges in global change research [15].

This paper therefore makes the case for studying the phenomenon of tourism as a socio-ecological system. It argues that a systemic approach of tourism and its environmental ramifications requires integration of tourism research and the environmental sciences and internal integration of the disciplinarily and geographically fragmented research field of tourism. A systemic approach also requires strong stakeholder involvement regarding problem formulation, problem analysis and implementation of solution strategies. Agent-based modelling is put forward as a promising integrative approach to understand how individuals relate to environmental change.

The remainder of the paper is structured as follows. Section 'The need for systems thinking and transdisciplinarity in tourism research' introduces the need for transdisciplinary research in tourism and the key challenges associated with that. Section 'Agent-based modelling' suggests agent-based modelling (ABM) as a solution to some of these challenges, highlighting examples of ABM application. Finally, section 'Taking stock and moving forward' signals a way forward for tourism sustainability research.

The need for systems thinking and transdisciplinarity in tourism research

Tourism is studied from numerous disciplinary perspectives, including geography, sociology, anthropology and economics, with limited integration. Faulkner and Russell [16] and McKercher [17] revolted against the dominant conceptualisation of tourism as a well-behaved phenomenon that can be controlled and managed. They emphasised tourism's nature as a complex phenomenon and system. A handful of authors, including Baggio and Sainaghi [18] and Becken [19], have proposed to study

tourism as a socio-ecological system (SES) or complex adaptive system (CAS) to capture the dynamics and complexity that characterise tourism's relationship with sustainability. The transnational character of tourism involves diverse social systems, such as socioeconomic and legal institutions, transportation, accommodation and attractions. These social systems rely on a range of environmental resources (e.g., biodiversity, land, energy, water) as well as sinks (e.g., atmosphere, ocean) and thereby contribute to environmental impacts and change. At the same time, environmental change is increasingly affecting the direction and volume of transnational tourism mobility. Taking these feedbacks into account is essential for tourism research in the Anthropocene.

Only a handful of studies have actually applied CAS or SES approaches to tourism in a sustainability context. Strickland-Munro *et al.* [20] and Ruiz-Ballesteros [21] focused on the interactions between protected areas, tourism and communities. Becken [19] explored the resilience of tourism sub-systems impacted by climate change. Lacitignola *et al.* [22] and Petrosillo *et al.* [23] studied the interlinkages between tourism destinations and the quality of ecosystem goods and services.

Global environmental change research, in contrast, has a well-established tradition of complex systems approaches. It also has a 30 year history of integration [24], progressing from disciplinary through multidisciplinary to interdisciplinary and then transdisciplinary research. Interdisciplinarity within the natural sciences started in the 1980s and 1990s, followed by the incorporation of the social sciences in the 2000s and 2010s and the current transition towards transdisciplinarity [25]. Whereas interdisciplinarity crosses disciplines but remains exclusively grounded in science [24], transdisciplinarity refers to the 'unity of intellectual frameworks that transcend disciplines and involves stakeholders' [26]. Transdisciplinarity enables researchers to better establish the role of human action and decision-making in environmental change. Stakeholder involvement is essential when addressing complex problems, to improve the problem definition and devise and implement strategies for improvement. A complex systems approach has been part and parcel of all three stages of integration, acknowledging the dynamic, non-linear and largely unpredictable nature of environmental change.

The sharp contrast between global environmental change research and tourism research in the uptake of complex system approaches can be partly explained by the specific characteristics of the tourism phenomenon and of tourism research. As an industry, tourism is notoriously fragmented and diverse, consisting of a variety of primary (e.g., accommodations, transportation, attractions) and intermediary (e.g., sales and marketing) segments. Members of the tourism industry hail from the public, private and not-for-profit realms, with substantial variations within each. Private enterprises, for example, can range from multinational corporations to family-owned and family-operated concerns. The continuing emergence of the sharing economy (think of Airbnb and Uber) has multiplied the number of stakeholders active on the supply side.

Also outside the tourism sector, the heterogeneity among tourism stakeholders is large. Tourism patterns and impacts emerge from the visits of billions of international and domestic tourists to countless destinations. Tourists and destination residents are critical stakeholder groups, each of which can exhibit widely differing motivations, preferences and behaviours. Moreover, the recent advances in communication technologies have relaxed many space and time constraints so that stakeholders traditionally out of the destination bounds are now actively engaged, making a destination an even more complex ecosystem. A tourist, in turn, often does not travel alone and decisions on where to go and what to do are typically made among multiple people, perhaps further influenced by additional layers of actual and online relatives, friends and peers. To complicate matters further, many stakeholders are not exclusively part of the tourism system. Restaurants and supermarkets, for example, cater to both tourists and locals. Fragmentation also characterises the tourism literature. Much of that literature focuses on discrete sub-sectors, locations, elements of the travel experience or events rather than taking a more holistic approach that crosses scales, boundaries and ecosystems.

The key characteristics of the tourism system, as outlined above — including its multiple and heterogeneous stakeholders and fragmented disciplinary approach — impose challenging requirements on the research tools used. Addressing the grand challenges of the modern day requires tools that: transcend disciplinary differences, integrating quantitative and qualitative knowledge from multiple domains; invite stakeholder participation; and explore the effects of potential developments and policy choices on society and the environment. In other words, we need transdisciplinary and exploratory rather than disciplinary and predictive tools, but such tools are largely absent from the methodological toolbox currently used in tourism research. Pons *et al.* [27], for example, note that 'one of the main challenges in climate change impacts studies has been to relate the physical impacts and changes in the environment with their human implications such as socioeconomic impacts or human responses.'

Simulation modelling of socio-ecological systems is particularly well-suited to 'advance the understanding of dynamic correlations among various human and environmental factors, including impacts and responses to environmental change' [28•], especially in cases where the potential for experimentation is limited. Sustainability encompasses both a goal state and the durability of this

state over time [29], model-based computational experiments are thus employed to explore possible futures [30]. There are several simulation modelling methods, such as system dynamics, agent-based modelling and discrete event simulation. Of these, system dynamics is arguably the most commonly used method in tourism research (see [31] for a recent example). In other fields, system dynamics (SD) has been used from the mid-fifties with the purpose of incorporating dynamic processes and events. SD models represent a system under study with a large number of attributes evolving in time. This evolution is mathematically formalised using difference or differential equations. SD has limitations when it comes to representing heterogeneity and social interaction. It is characterised by a lumped representation of processes. Agent-based modelling transcends these limitations of SD as it can represent not just an entire system, but each one of the elements interacting within that system and thus causing its behaviour. These so-called agents can all differ from one another. They can interact with each other and with their surroundings, with a rich repertoire of changeable behaviour rules, just like tourism stakeholders do in reality. We therefore argue that ABM represents a more accurate ontology of actual tourist systems and is a promising tool for tourism sustainability research.

Agent-based modelling

Agent based modelling (ABM) has been defined as 'the set of techniques [in which] relations and descriptions of global variables are replaced by an explicit representation of the microscopic features of the system, typically in the form of microscopic entities ('agents') that interact with each other and their environment according to (often very simple) rules in a discrete space-time' [32]. ABM is therefore one possible methodology via which to simulate the coupling of tourists, the tourism industry and other tourism stakeholders with the environment in which they operate so as to improve system-level understanding. ABM is a form of computational modelling that incorporates both agents (e.g., tourists, tourism businesses) and an environment (e.g., a tourism destination) and allows analysis of the range of outcomes resulting from interactions among these entities as they emerge based on individual decision rules or behaviours (e.g., a tourist choosing whether or not to visit a ski resort). The outcomes are emergent patterns of system behaviour that are not under any central control. A recent overview of existing and potential applications of ABM in a tourism context [33••] highlights its utility in a range of tourism planning, development and management contexts.

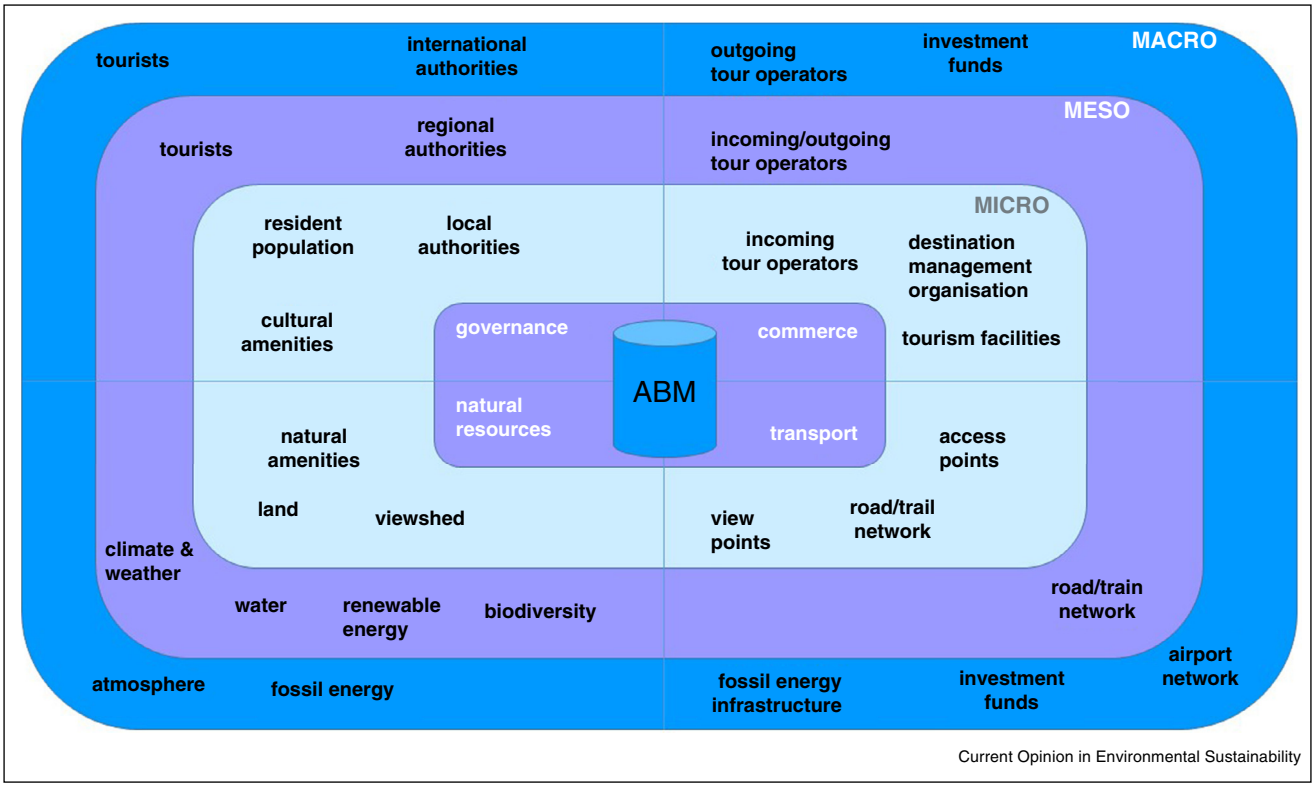
As described above, one of ABM's strengths is the coupling of multiple heterogeneous agents or stakeholders with environmental features (see [34]). Typical ABM studies consist of computationally intense, detailed dynamic simulations where many heterogeneous human and natural agents interact at multiple temporal and spatial scales. Agent-based modelling lends itself to graph and network analysis allowing not only to capture the network of flows between agents, but more importantly, to attribute heterogeneous roles and behaviours to the agents themselves [35]. In a tourism context, agents might include tourists, residents of tourism destinations, tourism businesses, marketing entities and government agencies, while the environments in and with which these agents interact would most likely be an attraction or destination, whether a specific site or resort, or a city, county, state or nation (see e.g., [36]). Figure 1 identifies possible relevant agent classes for the study of tourism as a social–ecological system across multiple geographical levels. The four quadrants capture the domains (or subsystems) that the agents can belong to: governance, commerce, transport (industry) and natural resources. The three bands capture the three geographical levels: micro (destination), meso (region) and macro (international).

Further model mechanisms could include such things as social contagion in destination choice and sustainability-related behaviour of tourists and of hospitality professionals. The boundaries of the model can be adapted to suit the purpose of the research question. For example, tourism boundaries employed in studies to date include the Canadian province of Nova Scotia [37], a well-established European skiing area [28•], an Italian Alpine municipality [38], a Portuguese coastal NUTS III region ([39]; NUTS is the Nomenclature of Territorial Units for Statistics, a European Union standard for referencing the subdivisions of countries for statistical purposes), an abstract representation of Antarctica [40], the Galapagos islands [41] and 109 European destinations [42•]. Further, ABM allows for a variety of exploratory uses, including as a tool to investigate hypothetical future outcomes of a specific policy change, to better balance tourists and resources [43], assess the impact of changing connectivity between destinations [37], or to refine understanding of a system to support further model development [44].

ABM also offers a platform for researchers working on different parts of the tourism system to share and integrate disciplinary information. Recent ABM projects on European alpine tourism (e.g., [27,28•,45]) demonstrate the success of the approach, uniting experts from geography, ABM, economics, climatology and behavioural science. Prior research on the supply side analysed the impacts on snow reliability of a number of extraordinarily warm winter seasons [46] and potential impacts in the future using climate change scenarios (e.g., [13]). Prior research on the demand side investigated potential impacts of climate change on the behaviour of ski tourists (e.g., [47]). Key insights were integrated with ABM.

Using ABM, Pons *et al.* [27,28•] combined weather scenarios (changes in snowfall, glacier retreat), changes to

Figure 1



Possible agent classes for the study of tourism as a social–ecological system across multiple spatial scales.

biodiversity and policy measures (artificial snowmaking). Their ABM approach enabled exploration of tourism demand and behaviours in response to climate change scenarios and snowmaking policies within the same geographical region. In this model, tourists were able to change location or activity. The results indicated what types of resorts under what circumstances would be affected in terms of changing visitor numbers and what the limits of artificial snowmaking are for ensuring sufficient snow for skiing. Moreover, Balbi *et al.* [38] found that in response to climate change, traditional ski-hill focused tourism may not attract more tourists and that energy efficiency improvements are necessary before adding any tourism infrastructure. These alpine tourism studies illustrate how ABM can provide an integrated story of the environmental challenges facing the socio-ecological tourism system while exploring adaptation measures (e.g., shift of activity, snowmaking).

Taking stock and moving forward

The impact of tourism on global environmental sustainability continues to grow. The relative eco-efficiency of tourism may be improving on some accounts, but the tourism's absolute environmental impacts continue to increase as a result of steeply growing travel volumes [9•]. Global environmental assessments for tourism have not yet been effectively connected to local developments and action perspectives for stakeholders. We argue that ABM can translate theoretical knowledge to practitioners and decision-makers. By taking a systems perspective, providing a platform for knowledge integration and stakeholder participation, and having a focus on individual stakeholders, ABM has the potential to link the exploration of grand challenges of sustainability and tourism with practical implementations and interventions at micro, meso and macro scales. It provides an interface between stakeholders to examine the impact of policies geared at a sustainability transition. In this way, ABM functions as a virtual laboratory to explore a range of possible futures. For example, with ABM, scenarios that industry deems 'uneconomical' can be tested and refined to both improve decision-making and stakeholder buy-in.

Though vital for tourism research, effective stakeholder involvement in ABM projects is difficult to achieve. Key bottlenecks include ownership, time requirements and variable expectations about the outcomes of ABM research. Stakeholders typically expect predictive results and point estimates, whereas ABM is better suited for the exploration of alternatives and providing range estimates of outcomes [48]. This contrast can give rise to disappointment amongst model users looking for quick

predictions to guide on-the-ground decisions. In addition, stakeholders are often unwilling to invest substantial amounts of time in research participation, in particular when the benefits for them are unclear and ownership is low.

A modelling approach that can link ABM more closely to stakeholders is the companion modelling approach. Companion modelling explores complex problems through a process of engaging stakeholders in problem definition, in understanding of the system, for design inputs and use of the (model) simulation and in the analysis thereof [49••]. This iterative process uses model simulations (often ABM) and/or role-playing games to represent the socio-ecological system. Companion modelling has been developed to further institutionalise stakeholder participation in resource management and facilitate the transition to transdisciplinarity [50], while increasing the transparency of model outcomes. At the core of tourism's complex system are the interactions of people and the environment. As such, stakeholder inclusion is often necessary to understand the human part of the system and develop policies that affect tourism practices. Companion modelling can support understanding of the socio-ecological system by favouring stakeholder inclusion, including their tacit system knowledge as well as preferences and gaining support for transformations of the tourism system.

In this paper we argue that ABM has both proven and potential value in environmental sustainability research for tourism. At the same time, it faces a number of challenges. Johnson *et al.* [51] discuss three categories of challenges regarding ABM adoption in tourism research: technical, communication and novelty. Other challenges relate to ABM's societal relevance and acceptability. Waldherr and Wijermans [52] review criticisms levelled at ABM by peers and distinguish lack of understanding and academic territorialism as causal factors. Yet there are real challenges as well. A key challenge in this category is validation. Models of complex systems are inherently difficult to validate as a result of the unpredictability of complex systems and also the lack of suitable independent datasets for comparison. With an increasingly instrumented world pushing the availability and use of 'Big Data', the challenge of appropriate data for both parameterisation and validation may be partially solved. Nevertheless, it remains difficult to determine whether the difference between observed data and modelled data represents a real result, is due to system complexity, or is an artefact of modelling error. Recent work in this area recommends the robust testing of all model parameters for sensitivity as a partial solution to validation concerns and as a way to increase confidence in ABM results [53,54]. Validation is further served by confronting domain experts with the system-level patterns generated by the models [55].

Conclusions

Tourism is a key manifestation of humanity's accelerating interaction with the environment, as part of the Anthropocene. Over the past decade, a body of literature has emerged on some of the main links between tourism and the global environment, including tourism's CO_2 emissions and water use and the climate change impacts on tourism resources. Important environmental challenges for tourism have been identified and partly quantified. These challenges have, however, not been sufficiently connected to stakeholder behaviour. An approach is needed that connects the various environmental issues and takes the social and environmental feedbacks into account: a systems approach.

Introducing systems thinking to tourism research is challenging in its own right. Tourism research has little experience with systems approaches and is strongly fragmented along disciplinary lines. Fortunately, tourism researchers can benefit from the 30 years of experience with systems thinking of the global environmental change research community. In addition, a range of complexity-based tools have become available that provide new opportunities. Of these, agent-based modelling (ABM) is found to be particularly suitable for studying tourism-environment interactions. ABM represents tourism's dynamics in a systemic, intuitive and individual-based way. It provides a window for linking together phenomena identified in separate case studies and a platform for involving researchers from diverse disciplinary backgrounds and stakeholders. ABM can build up from local case studies to look at macro phenomena, realising synergies by integrating and comparing insights. This resonates with McKercher and Prideaux's [56] observation that 'if trained well, [a new generation of scholars has] the potential to synthesize ideas from many perspectives to develop an epistemological basis for tourism studies'. In due time, tourism can become an example for other industries of how complex sustainability concerns can be addressed through the adoption of tools that support problem identification and analysis across scales, industries, jurisdictions and ecosystems.

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