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ABSTRACT

The need for sustainability transitions is widely recognised, along with a concurrent need for the evolution of knowledge systems to inform more effective policy action. Although there are many new policy targets relating to net zero emissions and other sustainability challenges, cities, regional and national governments are struggling to rapidly develop transformational policies to achieve them. As academics and practitioners who work at the science-policy interface, we identify specific knowledge and competency needs for governing sustainability transitions related to the interlinked phases of envisioning, implementing and evaluating. In short, coordinated reforms of both policy and knowledge systems are urgently needed to address the speed and scale of sustainability challenges. These include embedding systems thinking literacy, mainstreaming participatory policy making, expanding the capacity to undertake transdisciplinary research, more adaptive governance and continuous organisational learning. These processes must guide further knowledge development, uptake and use as part of an iterative and holistic process. Such deep-seated change in policy-knowledge systems will be disruptive and presents challenges for traditional organisational models of knowledge delivery, but is essential for successful sustainability transformations.

1. Introduction

Despite environmental policies delivering substantial benefits, most countries around the world still face persistent sustainability challenges in areas such as biodiversity loss, excessive resource use, climate change impacts, inequality, poverty and pollution risks to health and well-being (CBD, 2020; EEA, 2020b; IPBES, 2019; IPCC, 2018; UN, 2016, 2019). These impacts are manifest through the structures and functioning of systems of production and consumption – such as energy, food, mobility and the built environment (EEA, 2019). To achieve objectives embedded in the UN Sustainable Development Goals, the case for rapid, transformative changes in socioeconomic systems has been explicitly made

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by a range of science-policy initiatives and boundary organisations including FAO, UN Environment Programme, IPBES (Intergovernmental Platform for Biodiversity and Ecosystem Services), IPCC (Intergovernmental Panel on Climate Change), Future Earth, and the European Environment Agency (EEA). In short, achieving sustainability will not be possible without a rapid and fundamental transformation in the character and ambition of government responses, engaging diverse policy areas and actors across society in enabling systemic change (EEA, 2019; IPBES, 2019; Köhler et al., 2019). These rapid changes are increasingly spurred by new targets to meet net zero emissions as well as other environmental goals (e.g. the legally binding Environment Bill targets in the UK). Given this fast pace of policy development in concert with rapid societal and environmental change, there is a risk of unanticipated outcomes and hence an even greater need for a sound knowledge base and an adaptive approach to decision and policy making. Several studies have emphasised that our knowledge systems (i.e. the agents, practices and institutions that organize the development, uptake and use of knowledge) are inadequate for addressing the environmental and societal challenges we face in the 21st century (Arnott and Lemos, 2021; Cornell et al., 2013; Fazey et al., 2020; Kläy et al., 2015; Saltelli et al., 2016; van Kerkhoff and Szelezák, 2016), let alone for guiding major societal transformations at such pace.

In this paper, we provide a perspective from authors currently working in roles bridging the science-policy interface to describe specific changes in knowledge systems that are needed to effectively govern sustainability transitions. Specifically, we outline new knowledge architecture (defined here as knowledge types, processes of knowledge brokering and competency for the use of knowledge in policy decision-making; cf. Cummings et al., 2019; Kaipa, 2000; Kislov et al., 2017; MacKillop et al., 2020; McGonigle et al., 2020; Michaels, 2009) that need to be urgently implemented to inform timely and wise decisions. A key element of this is the shift towards a 'competence-based' approach that extends the traditional view of knowledge to also encompass the skills and attributes of those involved in rendering knowledge

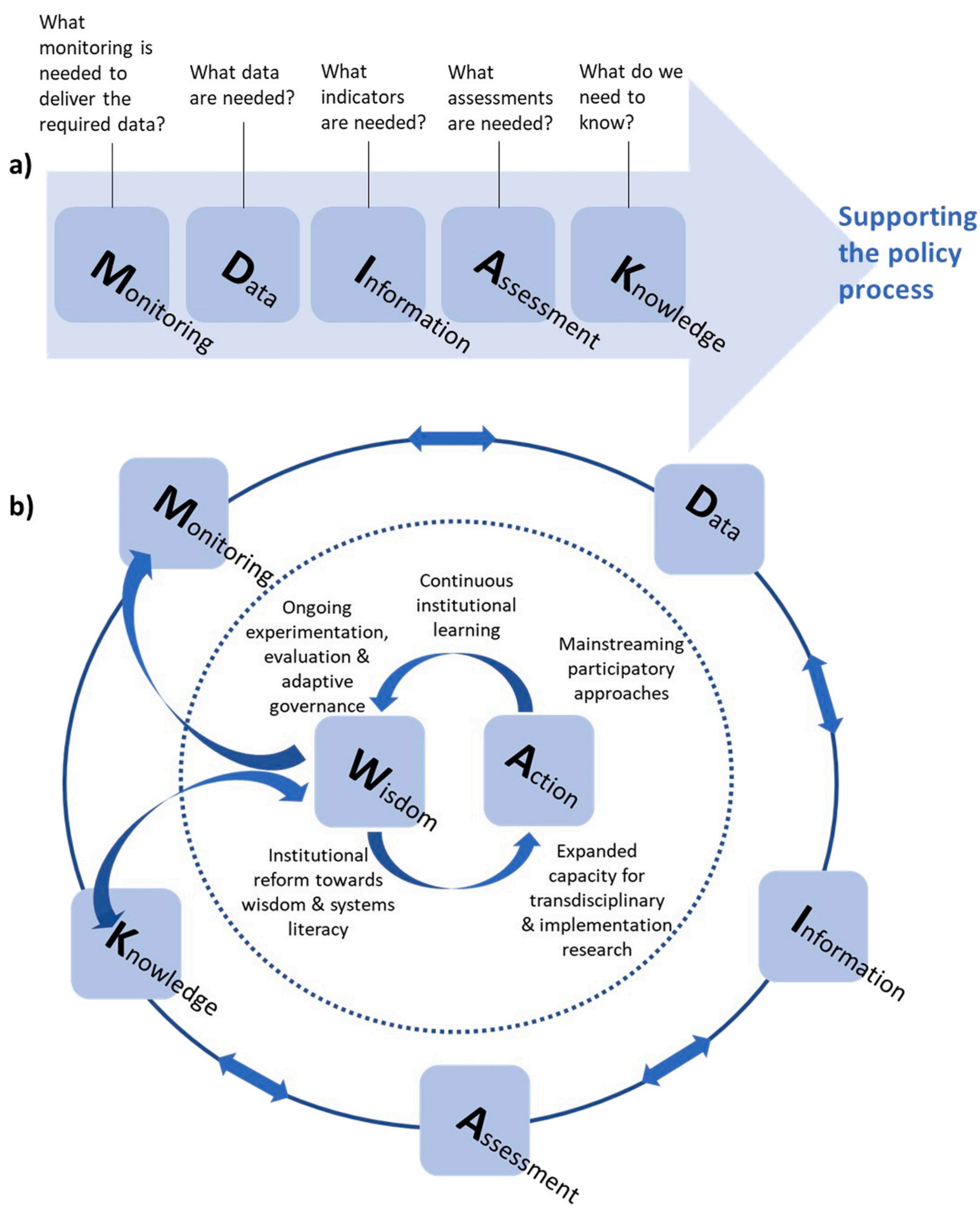

Fig. 1. Knowledge architecture for governing sustainability transitions. The 'MDIAK' framework developed by the European Environment Agency to help distinguish between the different phases of knowledge development to support policy processes (EEA, 2011; panel a). Panel b extends this with key considerations on how knowledge systems need to evolve to enable wise governance of sustainability transitions (see main text for further explanation).

'actionable' within policy and decision-making (Klett, 2010; McGonigle et al., 2020; West et al., 2019); and addressing knowledge development, uptake and use as an iterative and holistic process.

2. Knowledge to support policy and decision making

Our focus in this paper is on knowledge to support decision making and policy processes within government, but with recognition that this sits within a broader framework for polycentric environmental governance, prompting a need for the policy systems to engage diverse stakeholders. This broader engagement is essential to ensure that policy is targeted towards societal priorities and concerns, is effectively implemented and evaluated, and complements actions from other stakeholders. The lack of governments facilitating such engagement and appropriately devolving participatory decision making to regional and local levels is highly problematic in the context of the major changes need for sustainability transitions, as we will outline.

We focus on a case study here using the EEA, exploring a current framing of how knowledge links to policy decisions. The EEA is an influential science-policy boundary organisation with 32 member countries and 6 cooperating countries that provides independent information to support policy and decision making at European and national level. The EEA has characterised the different phases of knowledge development into a sequence referred to as the 'Monitoring, Data, Information, Assessment, Knowledge' (MDIAK) chain (EEA, 2011; Fig. 1a). Diverse organisations work at different points along this chain. For example, some specialise in providing long-term data collection (e.g., Copernicus services, International Oceanographic Commission and statutory national environment agencies) on which assessments are based. In many cases, these organisations are supported by national governments or international funding bodies, although in some cases (such as biodiversity monitoring) they are supported heavily by the third sector (Theobald et al., 2015). Citizen science schemes also increasingly provide additional monitoring resources (and develop knowledge for citizens; Bonney et al., 2016). Data are often then passed to boundary organisations such as the EEA. Following the synthesis of data into indicators and assessments, knowledge can be passed in turn to national governments and international bodies, such as the European Commission, to support the policy process (Fig. 1a).

Considering, the extent and quality of data gathering and integration into major international environmental syntheses (e.g. CBD, 2020; EEA, 2019; IPBES, 2019; IPCC, 2018; UN, 2016), one might describe these knowledge developments as science-policy success stories. In some cases, they have spurred high-level political action; for example, the European Green Deal (Bloomfield and Steward, 2020; European Commission, 2019). There are still gaps in monitoring and assessment, for example, most monitoring effort goes into understanding the state of ecosystems and impacts on people, with relatively little monitoring of the ultimate drivers of environmental degradation or into the effectiveness of societal responses (EEA, 2019). However, more important than just addressing gaps is the question of whether this traditional model of knowledge delivery can adequately spur and guide sustainability transitions (Maas et al., 2020)? In the face of wicked problems involving deep uncertainty, with values in dispute, high stakes and requiring urgent decisions (Funtowicz and Ravetz, 1993; Sediri et al., 2020), several studies have suggested that our knowledge systems are inadequate for addressing the environmental and societal challenges we face in the 21st century (Cornell et al., 2013; Fazey et al., 2020; Kläy et al., 2015; Múnera and van Kerkhoff, 2019; Saltelli et al., 2016; van Kerkhoff and Szezák, 2016).

New ways of funding and conducting knowledge gathering, beyond mainstream traditional scientific approaches, are being increasingly suggested (e.g. the Horizon Europe research programme; European Commission, 2020a; and Fazey et al., 2020), whilst science-policy boundary organisations are evolving to try to address new knowledge needs. For example, the EEA has developed a greater focus on knowledge needs around sustainability transformations (EEA, 2019, Parts 3 & 4) while the IPBES has an assessment on *'Transformative Change'*, and the European Commission's Joint Research Centre leads an *'Enlightenment 2.0'* research programme to understand the different drivers that influence political decision-making in the 21st century. Efforts are ongoing to expand knowledge gathering beyond traditional actors, such the university sector, whose outputs and diversity of viewpoints and values is often more influenced by their research focus rather than policy needs. The importance of indigenous knowledge sources is now increasingly recognised (Alexander et al., 2019; Díaz et al., 2018; Whyte, 2013), and solutions for societal problems are being generated all the time by individuals, businesses and civil society organisations, leading some researchers to ask how these can be collated by boundary organisations in order to share best practice around novel solutions (Maxwell, 2019). These trends reflect a growing recognition of the need for knowledge systems to "go beyond creating knowledge about the world to rapidly creating the wisdom about how to act appropriately" (Fazey et al., 2020).

Beyond the evolution of science-policy knowledge brokering, we argue that there is also a requirement for concurrent reform of government institutions, otherwise there can only be limited effective actioning of knowledge to deliver sustainability transformations. This may partly explain why progress towards sustainability transitions has been incremental. The current status quo is, in fact, a fragmented policy landscape with goals that conflict across sectors, limited evaluation and capacity for learning and poor interface with a research community that struggles to deliver actionable and timely knowledge to inform policy and decision-making processes.

To remedy this situation there is a need to work backwards from decision-making to better understand the context in which decisions are made, and identify various strategies for knowledge brokering that play well in those contexts (Cummings et al., 2019; MacKillop et al., 2020; Michaels, 2009).

3. Working back from policy needs: quick fixes versus systemic change

Substantial research budgets are dedicated to environmental science and sustainable development across the world (OECD, 2020), but they often focus on the monitoring-data-information-assessment elements of the MDIAK chain and neglect proximate knowledge needs for urgent policy decisions (although there are some exceptions, such as the EU Structural Reform Support Programme, which takes a more transdisciplinary approach to directing research for policy). This problem is exacerbated when funding is influenced by priorities from the organisations who collect and analyse data. To some degree, such input is sensible because these organisations have a clear view of the gaps in existing approaches. However, they are unlikely to see far beyond their own remit towards radically different types of data, knowledge and information that are genuinely needed for decision making (Cornell et al., 2013; Fazey et al., 2020; Kläy et al., 2015; Saltelli et al., 2016; van Kerkhoff and Szezák, 2016). Such feedbacks can 'lock-in' the status quo model of knowledge brokering.

With regards to academic research, funding agencies do work with governments to understand their needs. However, traditional models of research funding, with projects taking months to review and years to complete, and with multiple stakeholders rarely meaningfully engaged through this process, do not always deliver timely, relevant knowledge needed for policy decision making. Governments sometimes make efforts to share their research needs directly (e.g., UK government departments publish 'Areas of Research Interest'; UK Government, 2020), but there are often limited mechanisms to effectively operationalise such research by bringing together relevant policy teams with knowledge providers in a timely way (McGonigle et al., 2012).

Therefore, there are some clear easy wins for addressing deficits in science-policy knowledge systems to improve the delivery of timely advice for policy decisions. For example, innovations might include: i) greater capacity in government for dedicated staff working at the science-policy interface to articulate research needs to funding bodies, ii) secondments into government organisations from researchers and research funders, iii) synthesis research programmes and better platforms for science and policy to interact (Snoeijs-Leijonmalm et al., 2017), iv) improving incentive structures for researchers to engage with policy-makers and vice versa (Gibbons et al., 2008), and, v) more rapid short-term research funding linked to major policy decision points. Such approaches could deliver substantial benefits with only minor modification of the current knowledge system configuration. However, there is also a widespread recognition of the need for more extensive approaches to knowledge co-creation with a range of actors across society, and beyond standard knowledge providers such as universities (Cornell et al., 2013; Lang et al., 2012; McGonigle et al., 2020).

To go further than quick fixes, we need to find new ways to actively and continually guide sustainability transitions. To do that, it is useful to consider phases of sustainability transitions (Fazey et al., 2018a; Moore et al., 2014) and here we focus on three interlinked stages of: 'envisioning', 'implementing' and 'evaluating' (Fig. 2; Table 1). We explore how to put in place ideal knowledge architecture to address decision-making needs in each phase.

4. Organisational wisdom, adaptive leadership and systems thinking literacy

Governance of these three elements of sustainability transitions requires appropriate architecture for (socially and scientifically) robust knowledge and effective competencies that enable the 'best possible' decisions to be made for society. This means decisions that meet sustainability demands now and in the future, or, as framed in the renewed 2050 vision of the European Commission *"to ensure wellbeing for all, while staying within planetary boundaries"* (European Commission, 2020b). Making such decisions needs more than just data and intelligence; it needs wisdom and whole-system thinking. Ambrose (2019) describes how wisdom has always been important for human thought and action, but particularly so in the context of 21st century globalisation, which features highly complex, turbulent socioeconomic conditions and technological developments. We might add to this that, in the context of the urgent policy decisions which will dramatically reconfigure our social, economic and environmental systems, the capacity for wise decision making is essential. In the face of pressure for urgent action to address the sustainability crisis, decisions might be made that have adverse consequences by shifting burdens from one area to another. For example, historic biofuel policy to reduce climate emissions has arguably increased food prices and exacerbated habitat loss (Boersema et al., 2007; Searchinger and Heimlich, 2015). In the face of new legislation to meet net zero emissions in many countries, ambitious bioenergy plans are now back on the table. How can we avoid making similar mistakes?

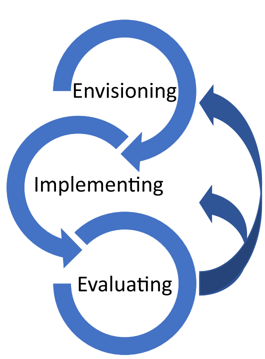

Fig. 2. Three interlinked phases of sustainability transitions. *Envisioning* transitions involves exploring sustainability issues from multiple stakeholder perspectives and co-creating plausible and normative visions for future states. *Implementing* transitions requires well-coordinated action at all levels of governance, across multiple sectors and by multiple stakeholders. *Evaluating* transitions requires a learning attitude towards both the choices made, operational targets, policy instruments and their effects (see Table 1 for more detail, including explanation of feedbacks).

Alternatively, without confidence that interventions will not lead to severe unanticipated consequences, policymakers may tend towards low-risk options. Such risk aversion leads to incremental gains, with 'safe' decisions being made in the short-term, but failing to make the necessary adjustments to navigate a sustainable course for society in the longer-term. Below we outline how several disparate research fields related to knowledge management, psychology and 'systems thinking' all have insights on developing knowledge and competency practices for effective decision making, yet there is a need to integrate these in the context of sustainability transitions. Several of the insights here come from a 2.5 year 'Systems Research Programme' within Defra (the UK's Department for Food Environment and Rural Affairs) involving four of the authors (THO, BD, GK, DM). The programme aimed to identify key gaps in systems approaches for UK environmental governance and highlighted both a need for enhanced individual competencies, which we summarise in this section and new institutional protocols, dealt with in Section 5 (e.g. better participatory processes to identify and balance multiple desired outcomes, developing appropriate implementation strategies that account for trade-offs and synergies, and designing highly adaptive policy in light of deep uncertainty).

4.1. Organisational wisdom and wise leadership

Wisdom can be conceived of not only in personal terms but also at an organisational or social level (Maxwell, 2019). Rowley (2006) defines 'organisation wisdom' as i) making sophisticated and sensitive use of knowledge; ii) using judgement that accommodates multiple realities and weighs the interest of multiple stakeholders; iii) taking into account wider social and ethical considerations; iv) exercising wisdom in decision making and the implementation of decisions; and v) taking a long-term perspective. Rowley (2006) suggests that organisations can set in place processes to develop organisational wisdom. One way to do this is through training leadership skills (Small, 2004). This can involve training for perspective taking and enhanced strategic thinking capabilities (Jacques and Clement, 1991), visioning and being able to take the long view, and being able to engage others in dialogue effectively (Hammer, 2002). Enhanced understanding of social actors and their relationships has been termed 'social intelligence' or 'interpersonal intelligence' (e.g. Zaccaro et al., 1991), and contributes to improved conflict resolution skills (Sternberg, 2019). These leadership skills allow other people's values and perspectives to be addressed in decision-making, and help contribute to the capacity to take the *right* action in a timely way (Bartunek and Necochea, 2000), i.e. wise leadership guides knowledgeable actions on the basis of moral and ethical values (Courtney, 2001).

In addition to wise leadership, practices can also be institutionalised into decision support systems for sustainability governance. Organisational wisdom involves both the collection, transference and integration of individuals' wisdom along with the use of organisational and social processes (e.g. structure, culture, routines) for storage (Rowley, 2006). A key aspect here is the ability of governance systems to facilitate multi-stakeholder interaction and incorporate moral and ethical values into decision making (Bierly et al., 2000). Courtney (2001) outlined how the complexity of decision-making is increasing with a growing awareness of ethical issues and increasing globalisation, which together increases the number of factors and stakeholder perspectives that need to be considered in organisational decision-making. Expanded participatory approaches involving a wide range of relevant stakeholders can help governments make decisions about pathways to sustainability by helping them to navigate difficult trade-offs, and incorporating plural

Table 1
Elements of knowledge architecture for effective decision making for sustainability transitions, in relation to three interlinked phases of sustainability transitions (see also Figs. 1b & 2). Note, certain elements of knowledge architecture from Fig. 1b have been grouped to avoid repetition in the table.

Knowledge architecture aspect	Interlinked phase of sustainability transitions:		
	Envisioning	Implementing	Evaluating
Mainstreaming participatory approaches and transdisciplinary implementation research	Transformation choices necessarily require deep engagement with a variety of societal actors beyond policy makers, to understand a plurality of values and norms and make choices about societal priorities (Cornell et al., 2013), prompting co-responsibility amongst actors involved, all the while ensuring coherent decisions towards a just distribution of policy effects. This requires innovative approaches to navigate societal values to feed into decision-making processes, achieving compromise and to reconcile visions across different spatial scales (Fig. 4; Ehnert et al., 2018; Newig and Fritsch, 2009; Svedin et al., 2001).	Effective coordination and integration capacity for polycentric governance of sustainability issues enables strong horizontal coordination between partners and vertical coherence based on the hierarchical nature of governance (Jordan et al., 2018; Svedin et al., 2001). For example, this may require multi-stakeholder fora to weigh options among technological and social innovations along with socio-economic factors including production and consumption patterns, for their desirability, feasibility, efficiency and effectiveness (Saltelli and Giampietro, 2016) in light of volatile and complex drivers (Bennis and Nanus, 1985), and developing new sustainability 'experiments' requiring coordination from multiple actors (Hildén et al., 2017)	Feeding back evaluation learning into both implementation decisions and decisions over the choice of the transition pathways for refining or tweaking ambition, necessary policy instruments and heightening coherence in line with established values. For example, this is likely to involve monitoring and evaluating the unequal distribution of costs and benefits arising from systemic changes (Reynolds, 2014), including the temporal horizon for dynamic costs and benefits.
Institutional reform for wisdom and systems thinking literacy	Mainstreaming systems approaches in government. Utilising foresight techniques such as visioning, scenario and back-casting as well as road-mapping. Facilitating new approaches to incorporate a plurality of views in developing specific spatial plans along different temporal scales – linking short-term action to medium and longer-term ambitions.	Implementing policy in the context of wider socioeconomic influences and global megatrends (EEA, 2020a); in particular, understanding the role of new technologies embedded within a wider sociotechnical system, and how implementation success can vary with context (e.g., extent of adoption across society). Implementation strategy will be multifaceted to address driving forces, pressures, state and impacts.	As well as grounded in ex ante analysis (foresight/futures), evaluation must also be an ex-post endeavour, examining policy success/failure to draw out useful lessons (e.g. the role of vested interests biasing policy processes, inertia, barriers, lock-in etc.; Dornelles et al., 2020). This involves evaluating degree of policy coherence and understanding drivers/barriers to heightened coherence (critically evaluating the integrated nature of policymaking;Reynolds et al., 2016)
Experimentation, evaluation, adaptive governance and continuous organisational learning	Knowledge systems that facilitate widespread envisioning of future sustainable states/trajectories and plausible future pathways allow monitoring and responding to current socio-political and socioeconomic dynamics in relation to these visions.	Coherence of implementation implies on-going monitoring of progress towards transformation, while proactively refining policies if progress is found to be insufficient (Olsson et al., 2006). Flexibility and agility in adjusting implementation priorities is necessary, under the constraint of significant and long-term investment needed to develop and scale up niche innovations. This may involve learning from unplanned 'experiments' as well an strategically designed interventions implemented in an volatile and uncertain environment.	Adopting a learning attitude towards both the choices made, operational targets, policy instruments and their effects. Continuous monitoring of the nature, pace, scale and outcomes of system-level interventions and outcomes is needed based on new indicators for the sustainability transition (Parris and Kates, 2003; Williams and Robinson, 2020). Evaluation requires openness to learning (e.g. accepting, understanding and acting upon failures in visioning, implementation and evaluation itself), and the recognition that transformation is ongoing adaptive process in response to an ever-changing environmental, technological and social context (Chaffin et al., 2014; Folke et al., 2005).

knowledge of values and ethics (Balint et al., 2011; Hanlon et al., 2012; and see Section 5.2 of this article for examples).

4.2. Systems thinking literacy

In concert to the development of wisdom studies spread across multiple academic fields of inquiry, there has been parallel development in many other disparate academic fields of ideas around 'systems thinking', especially with a focus on capacity and practice (Ison and Shelley, 2016; Reynolds et al., 2018). Systems thinking approaches are about taking a bigger-picture approach to problem solving by considering multiple perspectives and values of stakeholders, thinking about causes and consequences over larger spatial and temporal scales, and incorporating insights from consideration of the broader social, political, economic, environmental, legal and technological context (Fig. 3). Systems thinking considers multiple framings of situations, the relationships between key actors and processes in a system, often considering more complex feedback processes than normal reductionist or 'linear' thinking allows.

What we term 'systems thinking literacy' here refers to the capacity within organisations (including their ability to identify and work with other key actors) to take a systems approach to decision making (Fig. 3). This involves individual and team competencies, related to wise and 'adaptive' leadership approaches (Heifetz et al., 2009), along with improved organisational protocols around decisions. With regards to the governance of sustainability transitions, it involves capability in methodologies to understand interactions between suites of policies, and how policy success will be affected in the context of broader global megatrends they are implemented within. These methods are likely to include familiarity with statistical, process-based and agent-based models (and their coupling), expert elicitation, evidence synthesis, transdisciplinary participatory approaches and foresight approaches. The knowledge generated from such methods needs to be translated/co-developed to support the real-world decision needs of policy makers at different levels of governance: regional, national and supra-national (Reynolds et al., 2018). Systems approaches can also assist decisions by public, private and civil society sectors, although the primary focus of this article is on government.

5. Institutional reforms for sustainability transitions

To cope with the challenges of sustainability, insights from the

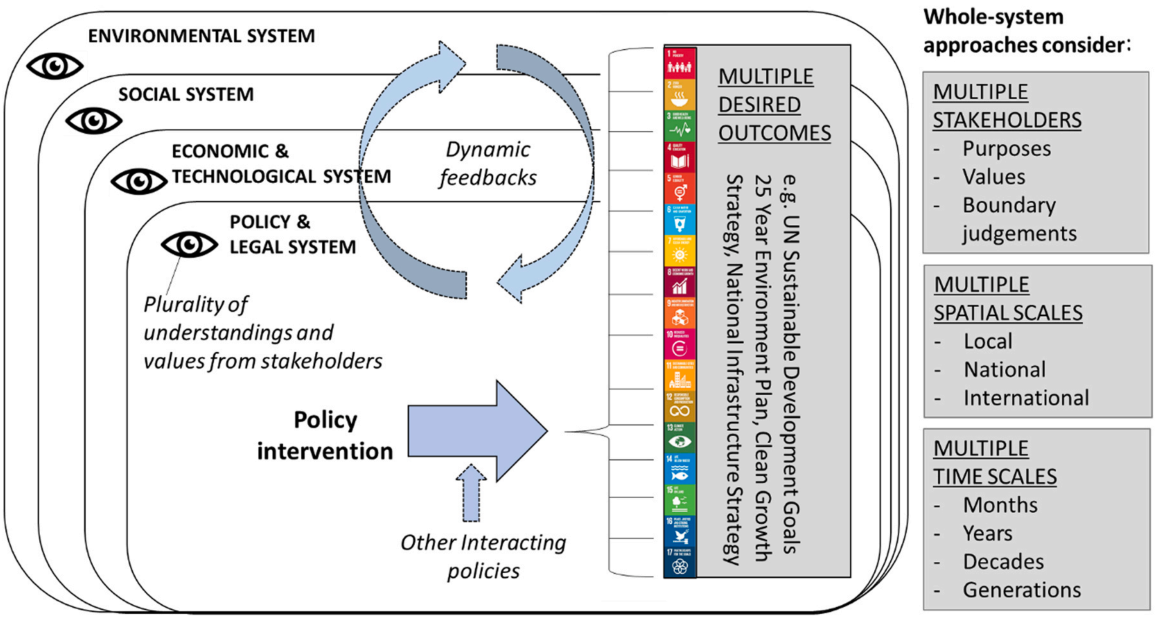

Fig. 3. Key elements of a systems approach to policy development for sustainability transitions.

research fields described above need to be considered in light of specific knowledge and competency needs for sustainability transitions. We have identified several key elements of how knowledge systems need to evolve to enable wise governance of sustainability transitions. These are shown in Fig. 1b and described in more detail below. In Table 1 we connect these to the three interlinked phases of sustainability transitions that are shown in Fig. 2.

Reshaping the knowledge-policy interface to implement such reforms can use insights from multiple traditional disciplines (such as political economy, sociology, institutional economics, behavioural psychology, philosophy and ethics; Köhler et al., 2019) and, crucially, these must be integrated into a broader transdisciplinary framework tied to key knowledge and competency needs around sustainability transitions. For instance, UNESCO (2017) describes 'key competencies for sustainability' as necessary for all learners of all ages worldwide including: systems thinking; anticipation; normative understanding and reflection; strategic competency; collaboration; critical thinking; self-awareness competency; and integrated problem-solving. To facilitate these competencies there is a need to overcome certain constraints, a key one being cognitive biases that operate at the individual level and can lead to ineffective practices becoming embedded in institutional protocols.

5.1. Overcoming cognitive biases to systemic thinking

To build capacity to facilitate wise, holistic decision-making will likely require training and protocols to overcome human cognitive biases. As an example, countries that initially responded better to the zoonotic disease COVID-19 in 2020 were those who had previous outbreaks of respiratory virus (Jefferson, 2020; Van Damme et al., 2020). The 'availability bias' explains why individuals are more prepared for risks that are very salient (such as those that happened recently). However, organisations should ideally not suffer from the same biases that influence individual human minds, but be designed to recognise and overcome these. Other biases relate to issues such as short-termism, confirmation bias, insensitivity to outcome probabilities and illusion of manageability, and many more (e.g. Das and Teng, 1999; Saltelli et al., 2020). Even political leaning (Jost et al., 2007; Zmigrod et al., 2021) and self-identity (DeCicco and Stroink, 2007) can relate to tolerance for ambiguity and uncertainty, which are key elements of managing wicked problems (Rittel and Webber, 1973); thus making insights from psychology highly relevant to sustainability governance (Oliver, 2020). It is possible to design organisational decision-making environments to reduce the influence of these biases. For example, the 'Long Time Project' funded by EU Climate—Knowledge and Innovation Community (KIC) worked with policymakers to identify 13 tools to enable them to integrate long-termism into their work (Burks and Saltmarshe, 2020). In terms of forecasting, training can help to improve probabilistic estimates from experts (Whitney et al., 2018) and combine them in a sensible way (Clemen and Winkler, 1999) and to be more salient of multiple outcomes needed from policies. However, many bureaucracies have tended to institutionalise cognitive biases (such as siloed decision-making), so in addition to competency training, systems thinking should be embedded into organisation design, for example through the allocation of responsibilities and evaluation of agents' performance.

5.2. Capacities to extend societal participation

Given the polycentric governance of sustainability (Jordan et al., 2018; Svedin et al., 2001), there is a need to coordinate participation from multiple stakeholders such as businesses, third sector, citizens and different levels of government, which can be informed by transdisciplinary action-research (Fig. 4; Cornell et al., 2013; Lang et al., 2012). These interactions are unlikely to form organically in a 'bottom-up' way with sufficient leverage to coherently influence policy, and therefore need *active facilitation* from government. This includes civil society engagement in knowledge co-creation through citizen science, journalism initiatives and democratic innovations like citizen juries (Smith, 2008) or using Structured Democratic Dialogue (Laouris and Michaelides, 2018). A key part of wise decision is making difficult trade-offs for the well-being of the whole of society in the longer term. Therefore, participatory approaches involving a wide range of relevant stakeholders are needed to understand what is 'best' for society (i.e. 'socially-robust' and legitimate; Nowotny, 2003), which cannot simply be presumed or dictated by policymakers who have their own sets of values.

Notwithstanding methodological choices to ensure representativeness (e.g. Holley, 2010), there are many benefits of using participatory approaches (Arnott and Lemos, 2021; Cash et al., 2003; Chilvers and Longhurst, 2016). Beyond eliciting values, providing intelligence of the acceptability of different policy options and lending democratic legitimacy to final decisions, they can develop a shared vision of ideal future

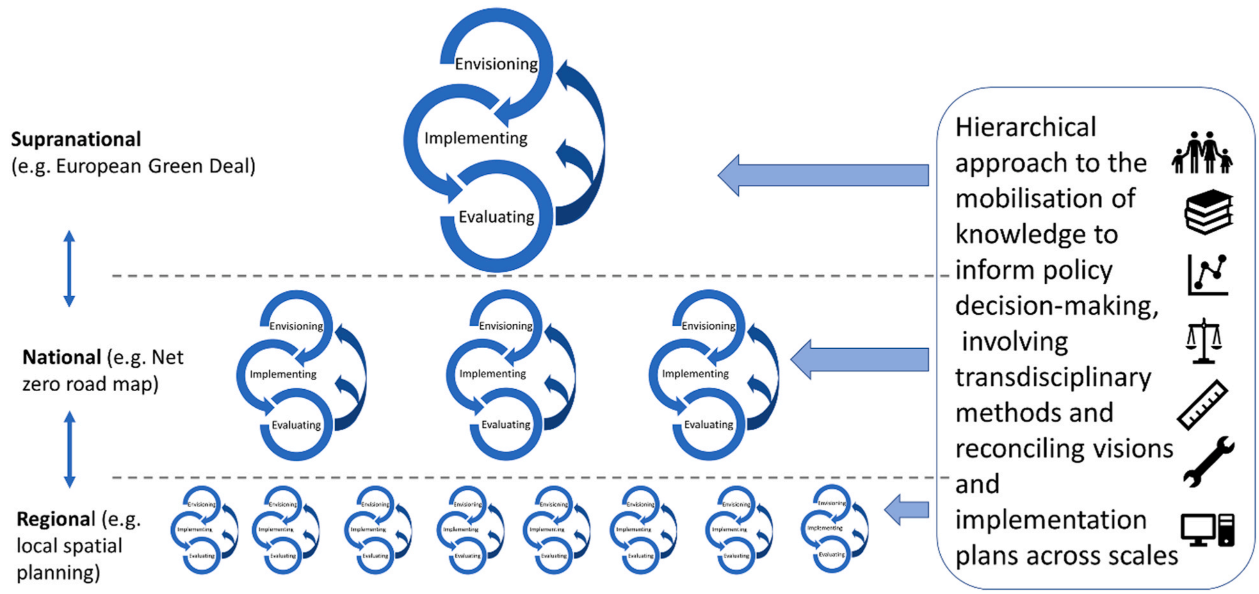

Fig. 4. Knowledge needs to address interlinked processes of *envisioning, implementation and evaluation* for successful sustainability transitions to occur at multiple levels of governance. These processes need organisational architecture that links knowledge brokers (e.g., within government, academic researchers, applied practitioners, science-policy boundary organisations) with government (local, national, international) and key stakeholders (e.g., businesses, third sector, citizens).

states reflecting local concerns and aspirations. They help to identify what type of future communities want, what trade-offs they are prepared to accept, who the losers are and how impacts can be buffered (Fazey et al., 2020; see Table 1 'envisioning'). Participatory approaches including diverse stakeholders enable more diverse forms of knowledge and knowing, such as practical, experiential and embodied forms of knowledge, as well as different perspectives, goals and values to be factored into policy decisions (Alexander et al., 2019; Díaz et al., 2018; Whyte, 2013). They can also improve the parameterisation of environmental and economic models through providing place-based insights not apparent from large-scale datasets. Additionally, they enable challenge of normative assumptions in models (e.g., how the future is discounted in economic models, or which aspects of biodiversity to include in ecological models). The involvement of stakeholders in policy decision-making processes can be empowering and may facilitate personal agency for other pro-environmental behaviours, plus there are also educational benefits from promoting engagement and joint-responsibility (Bonney et al., 2016; Bradbury et al., 2019; Charles et al., 2020; UNESCO, 2015).

There are several hotspots of good practice for facilitating participatory approaches in governance towards sustainability; for example, the European Commission multi-stakeholder platform for circular economy (EESC, 2017), the Just Transition Commission in Scotland (Just Transition Commission, 2020), and French Citizens convention on Climate (French Citizens convention on Climate, 2020). These initiatives involve government facilitating shared visioning, implementation and evaluation across a wide range of stakeholders, also including an appropriate consideration of just transitions through identifying and buffering potential 'losers' (Table 1).

A challenge for government is how to facilitate the broad uptake of such approaches across all regions, with appropriate mechanisms to reconcile regional, national and international strategy (Fig. 4; Chaffin et al., 2016). To some extent, shared visions for society have been attempted at the supranational level through the UN Sustainable Development Goals. Yet, at the local level envisioning is often limited to niche projects (e.g. Bennett et al., 2016; Pereira et al., 2019), with major constraints including a limited appreciation of the value of these approaches within government (potentially hampered by a fear of loss of control of political agenda and/or reputation risk), and limited resources and capacity within departmental budgets to facilitate them (Anggraeni et al., 2019).

If political barriers to mainstreaming these participatory action-research platforms can be overcome (i.e. enabling their broad uptake), then a next step is developing protocols to ensure they can effectively achieve vertical and horizontal coherence in policymaking. For example, in order to reconcile aspirations set at the regional level (e.g. flood protection, public greenspace access), with the national scale (e.g. coherent ecological networks, tree planting targets) and international scale (e.g. biodiversity restoration and greenhouse gas emissions), it may be possible to develop the approach used by countries for international greenhouse gas emissions accounting under the 2015 Paris Agreement. Under this Agreement, countries individually submit their Nationally Determined Contributions, outlining proposed climate change mitigation measures, which are collated to assess whether overall international emissions trajectories are commensurate with pledges to reduce global warming below 2 and preferably 1.5 degrees Celsius (UNFCCC, 2015). In a similar way, integrated spatial plans developed at the regional level (i.e. from a broad multi-stakeholder process combining participatory approaches and evidence analysis) can be collated to assess the degree to which they meet national and international targets. A back-and-forth between national and local planning already operates for housing development and transport infrastructure, but is poorly developed for designing landscapes to achieve multiple environmental and social outcomes. Instead, the tendency has been for centralised 'top-down' schemes such as the Common Agricultural Policy, which has been criticised for not meeting multiple objectives effectively and adapting well to local heterogeneity (Pe'er et al., 2020).

In terms of knowledge needs for mainstreaming participatory approaches to navigate sustainability transitions, there is a major role for ethicists, moral philosophers and psychologists to help understand *how and why* certain understandings of justice lead to different types of choices (and how this is affected by who is included/excluded in processes). They can also help understand the evolution of societal values and norms towards new technologies and cultural practices, and designation of responsibility for action (e.g., producers and/or consumers). There is a role for futures scholars and practitioners to enable foresight analyses, and a role for transdisciplinary facilitators (McGonigle et al., 2020; Rovenskaya et al., 2021) and policy makers to engage multiple stakeholders (O'Connor and Spangenberg, 2008). Integrated natural and social science is needed to develop anticipatory knowledge on the multiple outcomes and impacts of possible pathways to sustainability, including how policy success will be affected in the context of broader global megatrends they are implemented within. Finally, there is a role for political science, science and technology studies and innovation studies, which provide unique insights into conceptions of power, winners and losers, and how science, technology and innovation are framed and constructed in society (Fazey et al., 2018b).

5.3. Facilitating transdisciplinary implementation research

Despite progress in the social sciences about the best way to facilitate participatory approaches (e.g. Bradbury et al., 2019; Laouris and Michaelides, 2018) there remains a gap in how evidence feeds into these processes, and subsequently into policy processes. For example, in citizens assemblies, experts often present evidence to citizens, which can preclude citizens *directing* evidence gathering in a way that is much more tailored to local concerns and aspirations (recognising that the scientific process is always value laden; Funtowicz and Ravetz, 1993). These critical knowledge needs can then be addressed by researchers. For example, many governments have declared states of 'climate emergency' and/or adopted Net Zero emissions legislation and are now urgently seeking policy options to reduce carbon emissions, whilst balancing other objectives such as more equally distributed economic growth, public health and biodiversity restoration. The exact way a specific policy is implemented also affects all these multiple objectives differently. For example, with regards to policies that incentivise afforestation, the specific composition and configuration tree planting will determine flood protection, water purification, air quality, recreational value, landscape aesthetics, biodiversity and pollination services, as well as carbon sequestration, and may do so differently in different areas. How can citizens and decision-makers understand all these possible outcomes to make the best choices?

Following the identification of a long list of possible policy options through participatory deliberation with multiple stakeholders, a period of evidence gathering is needed to understand the potential outcomes of these policies. For example, in the case of different tree planting scenarios, process or statistical models might be run to estimate the multiple benefits gained and identify trade-offs (e.g. Binner et al., 2017; Gardner et al., 2020; Oliver et al., 2015; Redhead et al., 2017). In cases where quantitative models do not exist or are inappropriate (for example, because they have not been adequately validated, or because values are intangible), then anticipatory knowledge on outcomes may be based on ordinal scales and models and qualitative approaches, such as multicriteria analysis and expert elicitation. For example, changes to the aesthetic value of landscapes, and cultural benefits from tree planting might be captured in this way (Ridding et al., 2018). All these multiple outcomes for different scenarios, can next be considered concurrently by the multiple stakeholders, along with information on economic costs and other constraints and opportunities in policy implementation. A deliberative process results in narrowing down policy options, identifying further specific knowledge gaps, which can be addressed through subsequent rounds of tailored research. In such an iterative process, a final set of policy options is identified in both a participatory and evidence-informed manner. It should be noted that even with this evidence-informed participatory approach there is deep uncertainty in the multiple outcomes of favoured strategies. Hence, this befits an experimental approach to policy (Hildén et al., 2017); for example landscape recovery pilots on a regional basis (e.g. as implemented in UK Local Nature Recovery Strategy pilots).

Such approaches have significant costs to facilitate, which is especially difficult given regional governments are often highly resource constrained. For example, in the UK 65% of local planning authorities do not have access to an in-house ecologist (Association of Local Government Ecologists, 2012), let alone experts than can inform of a wide range of other social and environmental outcomes of policy decisions – in federal countries the situation tends to be much better. OECD countries have spent on average between 2% and 2.5% of Gross Domestic Product per annum on research and development over the last two decades (OECD, 2020). However, much of this funding is targeted to promote economic competitiveness rather than sustainability per se. Furthermore, the vast majority of public R&D funding supports primary science, with less for translation or implementation research (EEA, 2019; Hering, 2016). When criteria for judging science proposals is their state-of-the-art nature, then applied science cannot always meet this remit, despite its key importance in informing real-world solutions. Of course, there can be novel innovations in research application too. However, many elements of a successful framework (such as accessing datasets, and quantitative modelling protocols) can be developed centrally and used for multiple locations (otherwise there is huge duplication of effort if each place were to fund such innovation independently). Investing in bottom-up participatory approaches across multiple regions involves costs associated with technician time for evidence and data gathering, transdisciplinary researchers and facilitators to run the co-development process, logistic costs for venue hire, etc. Science councils may argue this implementation funding falls well outside their remit, whilst governments rarely allocate sufficient departmental budgets for commissioning such research. With new targets to meet net zero emissions and other pressing sustainability goals, hundreds of cities, and regional and national governments are struggling to urgently develop transformational policy, yet they lack sufficient knowledge architecture to supply implementation research to inform these policy decisions. We argue that this represents a major knowledge mobilisation crisis.

Finally, where knowledge to address such challenges is resourced and provided by organisations external to government, there is often insufficient cross-cutting structures in government to act as a 'landing pad' to coordinate such knowledge inputs. For example, where government policy teams are siloed into sectors such as water, biodiversity, waste, air quality etc., then research initiatives and knowledge brokers aiming to take a multi-objective approach (such as how nature-based solutions can provide multiple benefits), may find a lack of coordinated policy-team recipients for such input. In these cases, specific teams to bridge across disparate policy areas may be valuable. For example, the UK government's Department for Food Environment and Rural Affairs (Defra) implemented a 'Systems Research Programme' to identify improve systemic UK environmental governance. Beyond the formation of such teams, however, there also needs to be deeper reforms of government procedures as outlined in this article.

5.4. Adaptive governance based on ongoing evaluation

Governments will need to develop measurement and monitoring frameworks for evaluating sustainability transitions (Table 1). To keep actors accountable for their promises to promote sustainability transitions, evaluations of decided policies are required, but evaluations are even more important for learning and to develop policies and governance approaches that are better for achieving sustainability transitions. There are two main challenges with policy evaluations: to produce credible evidence and to produce evaluations that are actually used (Mickwitz, 2021). To produce credible evaluations for sustainability transitions, new data sources and new criteria, such as relevance for transitions, will be needed and empirical analyses should in evaluations be linked to transition theories and adopt system perspectives (Mickwitz et al., 2021; Reynolds et al., 2016). To produce evaluations that would actually be used, the same participatory processes discussed (5.2 & 5.3) in relation to governance should also be utilised in the evaluations. More specifically new indicators (both quantitative and qualitative) include indicators of pace, direction, scale and success of sustainability transitions that take account of the inherent systemic interlinkages between sustainability goals (Fazey et al., 2018a; Parris and Kates, 2003; Williams and Robinson, 2020). To answer questions like '*how well are we reducing environmental injustice?*' needs socio-environmental data, for example on the disproportionate burdens of air pollution on vulnerable communities. In this case, governments need to know, therefore, about the spatial and temporal distribution of air pollution; the causes and drivers of these outcomes; the distributional effects that result; and insight into the responses and interventions made and their relative success, including unintended side effects. Innovations in data and indicator design can be spurred by standard science funding (e.g., Horizon Europe), but the subsequent long-term collection and analysis of data needs to be picked up into organisational remits, with adequate budgetary support. Given the complex nature of sustainability challenges, any policy is unlikely to get it right first time, and in addition to using indicators there needs to be pro-active incorporation of flexibility and reflexive learning into policy design to prevent perverse policy 'lock-ins' (Chaffin et al., 2014; Folke et al., 2005; Olsson et al., 2006).

5.5. Continuous learning to guide organisational reform

Large organisations can be slow to evolve new cultures and ways of working, but there is an urgent need to proactively speed up learning approaches to meet the pace of the sustainability challenge (Tschakert et al., 2014). In line with Argyris and Schon's (1978) model of organisation learning, there is a requirement to go beyond just responding to changes in the environment without changing the core set of organisational norms (termed 'single loop learning'), to double loop learning where an organisation can adapt its learning processes by changing the core set of organisational norms or assumptions. Other researchers have described triple loop learning that occurs when one uses multiple realities to reframe one's own and other's experience in alternative frameworks (McWhinney, 1992; Reynolds, 2014). These critical explorations of different ways of sense making, questioning core purposes, and questioning how we know what is best (Fazey et al., 2018b) all require bold commitments in terms of learning capacity, the courage to contemplate organisational purpose, and capacity to enable organisational reform. To achieve genuine sustainability transitions, significant changes are needed in the social contract between government and society, incorporating transdisciplinary approaches to envisioning, implementing and evaluation transitions (Table 1). Not all effective approaches to sustainability will be planned and facilitated through government (Chilvers and Longhurst, 2016), and a capacity to learn from unplanned experiments will be important.

6. Conclusions

In the face of increasingly urgent sustainability crises, hundreds of cities, and regional and national governments are struggling to develop transformational policy, yet they lack appropriate knowledge architecture to inform their decision-making. Significant institutional reform is needed which includes reconfiguration of the knowledge and decision systems necessary to inform effective policies and interventions. We conclude that there needs to be a deliberate process of co-evolution based on adaptive governance and informed through systems-based and solution-oriented research, innovation and knowledge brokering. This moves away from linear models of knowledge delivery towards transdisciplinary research that interfaces in a more fluid way with policy cycles (cf. Fig. 1a and b). A reformed knowledge architecture would address critical knowledge and competency needs across the three aspects of sustainability transitions ('envisioning, implementing, evaluating'). This requires linking our developing understanding of social, economic and environmental systems with a deeper understanding of the policy system – itself a complex adaptive system that belies the simplistic linear or even circular models of policy-making (Hallsworth, 2011). And to help link understanding with action, we need a clearer focus on the full scope of competences for sustainability (e.g. as set out by UNESCO (2017)).

Beyond the consideration of monitoring, data, information, assessment and knowledge (the 'MDIAK chain; ' EEA, 2011), there needs to be greater focus feedback loops that enable organisational learning, and on fostering wisdom in decision making underpinned by a broad set of cross-cutting competencies for sustainability that further the principles of participatory action-research. This includes considering the capacity and motivations of policymakers, relationships between policy teams and knowledge brokers, training in systems thinking literacy, mainstreaming participatory approaches, and a renewed and broadened focus on implementation research for understanding multiple outcomes of policy decisions given place-based context. There must be a greater focus on evaluation, adaptive governance and continuous organisational learning; all guiding further knowledge development, uptake and use, as an iterative and holistic process. Such deep-seated change in policy-knowledge systems will be disruptive (Fischer and Riechers, 2019), and presents challenges for traditional institutional models of knowledge delivery (Gustafsson and Lidskog, 2018) but it is likely to be necessary for successful sustainability transformations.

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