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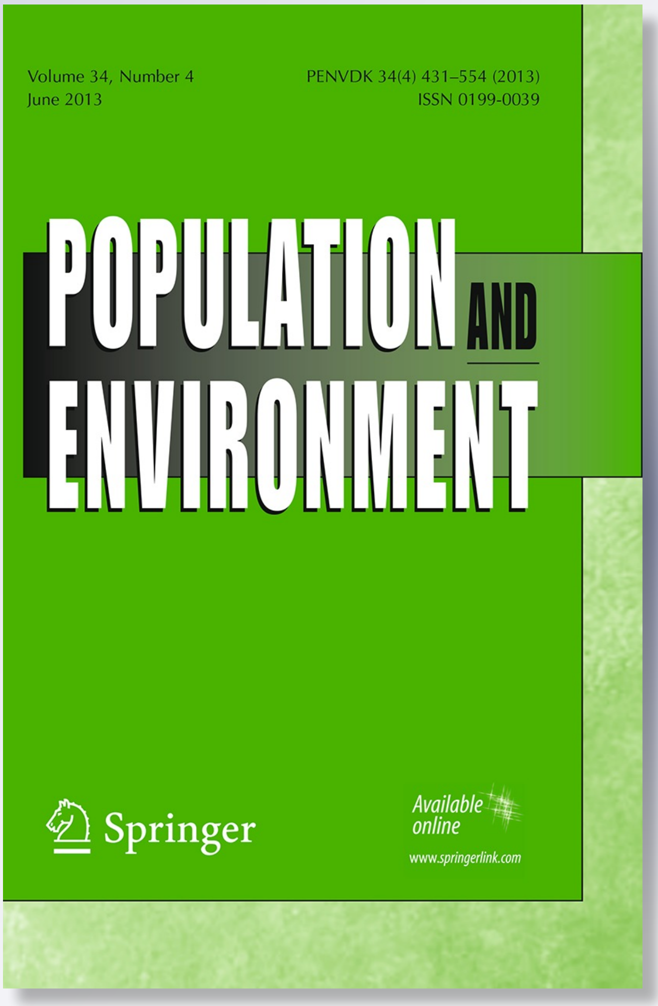

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ORIGINAL PAPER

Inter- and transdisciplinary approaches to population–environment research for sustainability aims: a review and appraisal

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Abstract The causes and consequences of demographic changes for the environment, and the possible ways of influencing population dynamics to achieve 'sustainability', have been the subject of many debates in science and policy in recent decades. However, the body of knowledge concerning relationships between population dynamics and sustainability is quite fragmented, dispersed over many disciplines, and encompasses diverse theories, paradigms and methodologies. This paper reviews four selected frameworks: linear, multiplicative, mediated, and system-theoretical approaches and perspectives. We represent how population–environment relationships are conceptualized, provide examples of research

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questions and accepted approaches, and critically assess their utility for different sorts of research for sustainable development. We note the growing recognition of the value of embracing complexity in population–environment research, and how this is consistent with normative aims of development.

Keywords Population–environment theory · Methodology · Political ecology · Sustainable development · STIRPAT · Sustainable livelihoods approach · Social-ecological systems · Transdisciplinarity

Introduction and background

Links between development, environment and demographic changes have been studied in depth for years, while links between population dynamics and *sustainable development* have been studied much less often. Attempts to empirically address connections between demographic factors and sustainable (or unsustainable) development often spark fundamental controversies in science and public discourse. One reason that is that demographic dynamics and impacts display a 'hybrid' structure: Social actions and ecological functions are closely coupled and it is difficult to unravel the causative processes. In this context, an electronic (cyber) seminar was organized by the Population–Environment Research Network (PERN) in February 2009 to stimulate discussion around theoretical and methodological issues in linking and analyzing population dynamics and the environment. This article draws on background papers and discussions during the seminar on major theories, the types of problems each approach is suited to address and new directions.[1] Several guiding questions oriented the discussion: Does the respective approach explicitly refer to a specific theory? Which specific research questions are addressable with the respective approach and by which methods? How are temporal, spatial, and social scales accounted for? At which level (micro-, meso-, macro- or multiple levels) is the analysis applied?

Theoretical and methodological approaches in population–environment research

According to the conventional wisdom, population growth in developing countries is regarded as a major cause for ecological degradation and natural resource depletion. Alternative perspectives reveal more nuanced, context-specific interactions, calling attention to the variations in demographic structures and dynamics

[1] In this paper, we refer to the background paper of this seminar (Hummel et al. 2009), the expert statements of the invited panelists (Aggarwal 2009; Knight 2009; Liu 2009; Murphy 2009a, b; Zulu 2009) as well as individual contributions of other participants of the cyberseminar to the discussion. The full discussion of the cyberseminar including the several panel contributions is documented at http://www.populationenvironmentresearch.org/seminars022009.jsp. We wish to acknowledge IUSSP and IHDP as co-sponsors of PERN and the support of the Institute for Social-Ecological Research (ISOE) for the support of this seminar and CIESIN's SEDAC project for hosting the network.

around the world. Given the diversity of phenomena, interrelationships and problem descriptions, the interactions between demographic changes and environmental problems might be considered as 'unstructured problems' (Klein 2004): The human part of human–nature interactions includes social, economic, institutional and technical developments, as well as norms, power constellations, and patterns of needs. Thus, they feature divergent values and knowledge in a context of intense debate. Both the epistemological and ethical dimensions of these discussions are characterized by uncertainties (about what the future will bring), ignorance (we don't know what we don't know) and contested knowledge (ambiguities and differing priorities among stakeholders). At the same time, the demands for more informed and timely political decision making are high. How does current population–environment (P–E) research address these issues?

In recent decades, P–E research has advanced intellectually and in praxis. It now spans different scientific disciplines, including demography, geography, economics, anthropology, and ecology.[2] By virtue of its pluralistic nature, P–E analysis comprises a variety of theoretical perspective and methodological approaches. We distinguish four different perspectives (after Marquette and Bilsborrow 1999): linear, multiplicative, mediating, and system-theoretical perspectives (see also VanWey et al. 2005). Below, we review these perspectives and discuss their utility, merits and limitations for different aims. We find it useful to link these major theoretical approaches to paradigm shifts in the sustainability and human development debate. Table 1 outlines these paradigms.

Linear perspectives

The term 'linear' originates from the Latin word *linearis*, which means pertaining to or resembling a line. Linear perspectives assume a direct, causal and deterministic relationship between population and environment. Malthusian and neo-Malthusian approaches are of this type. Largely developed by ecologists assuming equilibrium dynamics, they have featured theories and methods for assessing human carrying capacity and limits to growth (Hardin 1968; Fearnside 1986; Meadows et al. 1972; Ehrlich and Holdren 1971). These models underlie classic approaches to Sustainable Development (first row in Table 1). Population pressure, mainly size and growth rate, is a major and obvious culprit in visible environmental degradation and impoverishment. Public and political debate emphasizing population growth as a (if not *the*) major cause of ecosystem degradation still prevails (Millennium Ecosystem Assessment 2005; The Royal Society 2010), highlighting the urgency of reducing population growth and fertility rates in the South through population policies (de Sherbinin 1995; see also Domingo 2008).

[2] Today, population–environment research comprises a multitude of themes, for example, population, poverty and environment (Bremner et al. 2010), migration and the environment (Adamo and Izazola 2010), or population dynamics and tropical deforestation (Carr et al. 2006)—to mention only some of the diverse subjects. Since our focus is on theory and conceptual approaches of P–E research, a review on the different research topics would go beyond the scope of this paper.

Table 1 Normative development paradigms, allied P–E theories, and ecological and population factors

Development paradigms and definitions	Allied and compatible P–E theories	Treatment of ecological sustainability and population factors
Classic Sustainable Development (1980–) Development should 'meet the *needs* of present without undermining the ability of future generations to meet their needs' (World Commission on Environment and Development 1987)	Linear, neo-Malthusian Multiplicative: IPAT, STIRPAT Mediated: markets, prices, perverse subsidies, households	Contemporary life characterized by modern, mass-consuming societies is to be sustained over time, aiming to balance 'social, ecological, and economic' aspects in each country. Resource scarcity is the main environmental concern. Population factors are usually characterized as size/growth rates and demand on scarce resources (Malthus 1826; Ehrlich 1968). Questions raised are as follows: How to supply basic 'needs' (vs. wants) with growing populations? How many people can the resource base support? (Cohen 1995). Relevant data: demographic indicators, economic indicators, resource stocks, green accounting to capture externalities Quantitative, demographically rich approaches dominate at macro-level. Qualitative inquiry is common at community level. No single P–E methodology links quantitative and qualitative data and subjective perceptions; the diverse approaches within sustainable development schools reflect distinct ideological schools of thought. Reducing population, however, is accepted as a 'win–win' proposition that avoids social, political, economic and ecological conflicts. (UNFPA 2011)

Table 1 continued

Development paradigms and definitions	Allied and compatible P–E theories	Treatment of ecological sustainability and population factors
Critical Post-Developmental Alternatives (1980–) Seeks locally determined livelihoods and definitions of well-being; critiques mainstream, western, top-down 'development' and instead privileges locally determined actions to overcome poverty, inequality, exploitation that exist due to power imbalances in global post-colonial society (Sachs 2010; Escobar 1995; Ferguson 1990; Mosse 2005)	Dependency schools of thought (delink with Western societies, reduce northern consumption) Sustainable Livelihoods approaches (focus on assets and capabilities required for a means of living, strong emphasis on vulnerability context and role of institutions) Political Ecology (integrative; contextualized by social, economic, ecological factors; developing-country focus)	Diverse local ways of life, knowing and being are to be sustained, in contrast to uniform mass consumption. Population is rejected as a significant factor in explaining environmental degradation and poverty; population control movement reflects hegemonic power of US and European development actors. Instead, environmental degradation is result of exploitive relationships. Challenges conventional wisdom of implicit causality (i.e., poverty-degradation nexus); explicit attention to power at all of society in relation to relevant knowledge and access to goods Different lenses and voices enter sustainability debates: 'What should be sustained for whom, and how?' must be addressed by communities, and requires de-linking with hegemonic development apparatus (Sachs 2010). Globally, inequalities in the supply of services and goods exist due to power imbalances—these call for higher consumption (by some) as well as lower consumption (by the North)

Table 1 continued

Development paradigms and definitions	Allied and compatible P–E theories	Treatment of ecological sustainability and population factors
'Human Development' (1990–) Development means expanding 'freedoms to do more and be more in ways that one has reason to value' and enhancing capabilities rather than seeking growth or income. This is based in the Capabilities Approach of Amartya Sen (1999; 2007), enriched by Sabina Alkire (2002) and others, and enshrined in the UNDP in the Human Development Reports (UNDP 1990). See also Nussbaum (2011), Nussbaum and Sen (1993)	Mediated models: emphasis on universal values, just social institutions PEDA, Supply Systems (essential for fulfilling capabilities)	A range of human freedoms are to be sustained; the environment is fundamental to supplying freedoms, but is not explicitly addressed in the theoretical formulations. Demographic factors are not specified, but a focus on 'quality' (health, education) is intrinsic. Sen (1999) recognized that resource limits might be a fundamental constraint on human development. Research questions that arise: Which aspects of whose environment are to be sustained, and for whom, and for what purpose (with the end being that of enhancing capabilities)? This varies in relation to place, and whether local resources, global biodiversity, or pollution (greenhouse gases) are being considered. Cultural values and historical knowledge count, as well as scientific information. The priorities among different capabilities are unspecified and are to be worked out through public processes

Table 1 continued

Development paradigms and definitions	Allied and compatible P–E theories	Treatment of ecological sustainability and population factors
'Dynamic Systems' Approaches (2000–) Development is a process of navigating and choosing among different values, among agents functioning within complex adaptive systems characterized by nonlinearity, feedback loops and forms of incertitude (Scoones et al. 2007; Leach et al. 2007, 2010)	Political ecology Systems-feedback Supply systems CHANS	Ecological factors reflect dynamic ecosystems, services and interactions with human and other populations. Many human demographic factors (quantifiable variables of size, change, location in space, interactions and movements) are relevant at different scales. Subjective information is relevant since the aim is to promote human well-being (especially among the poorest), while sustaining valued properties and system attributes such as ecological functioning, social equality, and resilience. Questions and challenges include identifying the systems, boundaries and relevant properties, and which properties are valued and to be sustained. Politics and power differentials are explicit in different 'framings' of the problems by different agents in a context of uncertainty: How are these subjective points of view to be reconciled? Methodologically, diverse research approaches are needed for greater understanding and policy-relevant knowledge, that is, simulations (to model complex system dynamics over time), interdisciplinary case studies to understand relevant systems and 'broad and open appraisals' (Leach et al. 2010: 112) for identifying potential pathways

The general thrust of the P–E literature today, however, has evolved considerably from these simplistic debates. Direct causal explanations are viewed as 'reductionist': They oversimplify complex realities and are thus not very instructive (de Sherbinin et al. 2007; Hunter 2000; Lutz et al. 2002a; Jolly 1994). However, contributions from the natural sciences regarding critical thresholds and limits of ecosystems or natural resources do need to be taken into account in P–E studies (see for example Rockstrom et al. 2009). These natural-scientific analyses cannot be automatically dismissed or labeled 'neo-Malthusian' implying a linear and simplistic causality, as we shall see.

Multiplicative approaches: IPAT and STIRPAT

In multiplicative approaches population is central, but linked to economic activity and technological factors (see row 1 in Table 1) associated with sustainable development. One well-established model is IPAT: Environmental impacts (I) are the product of population (P), affluence (A), and technology (T) (Ehrlich and Holdren 1971). IPAT models of 'sustainable development' focus on reducing population pressure on the environment through improved technologies. This model has been the subject of much debate, because (among other reasons) it does not account for interactions *among* the terms. It also omits explicit reference to important variables such as institutions, culture, and social organization, which are considered important variables (Curran and de Sherbinin 2004).

Stirpat

In light of such criticism, scholars have refined IPAT (McKellar et al. 1995; Preston 1996), for example, by referring to non-demographic concepts such as the analysis of material flows and consumption research. Some have combined a stochastic form of the model with the ecological footprint concept, leading to the STIRPAT-approach (Dietz et al. 2007). STIRPAT stands for Stochastic Impacts by Regression on Population, Affluence, and Technology. It comprises a theoretical framework (SHE—Structural Human Ecology), a composite of first principles derived from IPAT, and a research program distinct from, though inspired by IPAT (Dietz and Rosa 1994).

STIRPAT retains the ecological foundation and multiplicative logic of IPAT, but enhances it by (1) allowing for estimation of the net effect of anthropogenic drivers on the environment, (2) allowing for hypothesis testing, and (3) incorporating other theoretically relevant variables including political, social, and cultural factors (Knight 2009). It is thus 'an analytic frame for disciplining conceptual models with empirical tests' (ibid.).

Attention to context is achieved by adding theoretically relevant control variables to the model. Demographic characteristics other than population size can be included such as age structure, household size, and urbanization (Dietz and Rosa 1994; Dietz et al. 2007; Knight 2009). While most STIRPAT analyses have been applied at the country (macro-) level, the model is theoretically applicable to any spatial scale, such as cities. Furthermore, it is not confined to any specific environmental threat, but can accommodate any impact variable. The research program of STIRPAT is explicitly theory oriented and refers to structural human ecology (SHE). This theoretical framework conceptualizes the relationships between society and the environment as the human ecosystem that comprises four interacting components: population, social organization, environment, and technology (Duncan 1966). SHE emphasizes the role of population size, growth, density, and structure in explaining environmental impacts. Biophysical factors such as biogeography and climate are also considered important contextual factors conditioning the social structural drivers of environmental impacts (Knight 2009).

STIRPAT can be considered as an aggregated version of Coupled Human and Natural Systems (CHANS) (Liu et al. 2007a, b; Rosa et al. 2010, see the section below). The model can test hypotheses about population–environmental changes, such as that the proportion of elderly persons in a population is associated with greater total energy consumption. Using data from 1960 to 2000 for 14 countries of the European Union, for example, York (2007) found that the proportion age 65 and over has a significant, positive effect on total energy consumption, controlling for total population, affluence, and urbanization.

STIRPAT's multiplicative perspective reveals that for impacts on the environment to be reduced, one needs to look beyond population to address rising affluence and technology, such as through improved energy efficiency. One weakness is its focus on macro-level analysis. Furthermore, all variables must be reduced to the parameters that can be incorporated into a multiple regression equation. Factors that cannot easily be quantified, such as culture and institutions, are necessarily omitted. Even certain environmental issues such as water pollution and land cover change cannot be incorporated because of lack of adequate data. Although superior to simpler linear approaches, this approach is still reductionist, omitting a range of environmental issues, mediating variables, and contextual factors that lend richness to other branches of P–E studies.

Mediating perspectives: Boserup, Sustainable Livelihoods, and Political Ecology

Mediating perspectives posit that there is no direct, causal relation between population and environment. Instead, interrelated and 'mediating' factors such as policy context, science and culture link population factors with environmental outcomes. These approaches are consistent with more nuanced approaches in Sustainable Development (row 1 in Table 1), as well as with critical development thought. Figure 1 presents a conceptual framework for the relationship between population and environment.

In recent empirical studies, population dynamics have been unpacked and disaggregated. Studies have analyzed specific population changes (e.g., in density, composition, numbers, sex/age structure, and life histories) and their impacts on specific environmental changes such as land degradation, deforestation, or climate change, etc. (see for example Liu et al. 1999a, b; Caldas et al. 2007; de Sherbinin et al. 2007, 2008; O'Neill et al. 2010).

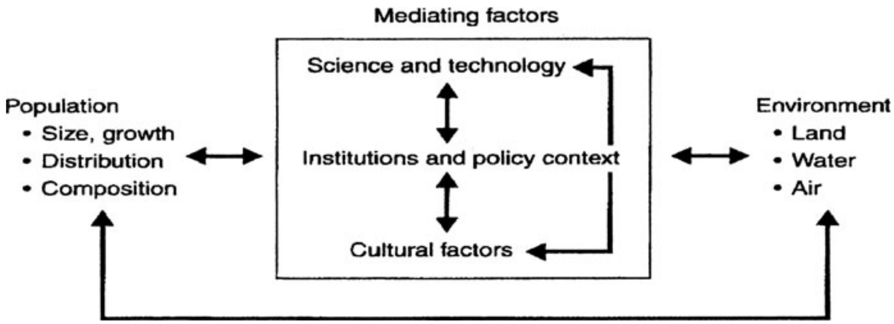

Fig. 1 Mediating variable approach. *Source*: De Souza et al. (2003: 14), Hunter (2000: 4)

Already Boserup (1965, 1981) and Simon (1986) emphasized the role of technology, institutions, market, and policy contexts in framing the population–environment nexus. The mediating perspective emphasizes that P–E dynamics are dependent on contextual factors. These include macro-economic policies, globalization, resource exports, institutions governing resource access plus local or region-specific dynamics. These perspectives are close to the theory of social embeddedness (Granovetter 1985), a reminder that population–environment relationships do not happen in a vacuum (Adamo and Guzmán 2001). The development-dependency approach is characterized by a critique of the prevailing model of development. International economic and political power constellations play a large role in shaping North–South dependent relationships. These have effects on population development and the environment (Marquette and Bilsborrow 1999; Hartmann 1995; Blaikie and Brookfield, 1987). Dependency theory, political economy, and other critical schools fed into critical political ecology approaches to understanding human–environment relationships from the ground up. The sustainable livelihoods framework—arising out of farming systems research and work with rural communities—emerged as one popular, practical approach. These two post-development theories of population–environment interactions are described in the next sections.

Political Ecology

Political ecology refers to a collection of theoretically related approaches that seek to make more explicit the interacting political and ecological processes that operate at different geographic and temporal scales. Their interactions shape local environmental problems and affect the options available to local decision makers to resolve these problems (Zulu 2009). It emphasizes historical and structural factors, incorporates spatial and temporal dimensions, and calls for different levels and scales of analysis (Gutmann et al. 1996; Little 1994; Schmink 1994; Blaikie and Brookfield 1987; Stonich 1989). Political ecology focuses on the recursive relationship between society, population, and the environment, seeking to disentangle the ultimate, underlying causes of social-ecological problems such as the co-occurrence of poor people and environmental degradation (Jolly 1994). Analysis focuses on mutually constitutive dynamics of nature and society from a critical and actor-oriented perspective. Common themes are the links between political marginalization and environmental degradation, the impacts of differential power on resources access, gender dimensions of social-ecological problems, a materialistic critique of capitalism and neoliberalism, and social justice turn and social movements (Robbins 2012; Watts and Peet 2004).

A classic example is Leach and Mearns' (1996) *The Lie of the Land*. The authors counter powerful but simplistic orthodox narratives ('received wisdom') among researchers, development professionals, policy makers, and the media of widespread population-driven environmental degradation in developing countries. They mixed natural and social science research methods to examine social, cultural, political, technological, demographic and economic factors in relation to observed landscape characteristics. The study demonstrated that population impacts were complex and context specific. Population growth was often only one of several other proximate causes shaping P–E problems. They blamed such P–E orthodoxy for problem misdiagnosis and misguided 'one-size-fits-all' Malthusian policies when multi-faceted, context-sensitive interventions were called for. Adding to the methods mix additional, sophisticated analysis of remotely sensed images of landscape change and 'thick' ethnographic contextualization, Fairhead and Leach (1996) further challenge the received wisdom. They revealed that 'forest islands' in the West African savanna were not remnant vestiges of pristine closed forests destroyed by growing populations, but were in fact created from grasslands by the local communities. Susan Stonich (1989) demonstrated that widespread environmental degradation in Central America was due to patterns of agricultural development driven by demands of capitalist accumulation, rather than population growth. In Machakos, Kenya, a landmark study by Mary Tiffen et al. (1994) showed that population growth, in the context of market opportunities and enhanced information, is consistent with environmental recovery; it spurred technological and capital investments in land conservation resulting in more income and less erosion.[3]

Political ecologists attempt to avoid the Malthusian trap by considering not only population growth, but also spatial patterns, mobility, household composition and life trajectories. P–E interactions are contextualized in a set of social (including demographic), economic, and ecological causal and mediating factors operating in a particular (localized) area, and 'whose outcomes produce distinctive problems and suggests particular solutions' (Zimmerer and Bassett 2003:1).[4] Some political ecologists even suggest that environmental problems in the developing South often are 'less a problem of poor management, overpopulation, or ignorance, as of social action and political-economic constraints' (Peet and Watts 1996: 4).

[3] Thus, one of the questions a political ecologist might ask is 'Under what conditions does rapid population growth lead to environmental degradation or recovery?'

[4] For instance, a nexus of high (urban) population, poverty, and strong market forces can set limits to the success and suitability of the all ascendant and ubiquitously adopted community-based natural resources management approaches in the developing South by providing 'irresistible incentives' for natural resource (e.g., forest) 'mining' and raise 'transaction costs' of collective action 'too high to sustain' community resource management intuitions and sustainable resource utilization (Zulu 2006: 248).

The current status of political ecology as a collection of holistically oriented, critically informed approaches has both strength and weakness. Political ecological analysis draws on various disciplines and (potentially) achieves social-biophysical integration and transdisciplinary thinking. However, the diversity of objectives, epistemologies, and methodologies makes it difficult to find a coherent theoretical approach (Walker 2006: 384) or common thread running across it (Robbins 2012). Some consider this 'looseness' the Achilles' heel of political ecology, since it undermines the broader relevance of political ecological analysis for policy makers. Critics also point to an over-emphasis on either politics or ecology (Robbins 2012; Walker 2005, 2007). Local people are often portrayed as victims instead of agents. Conflicts and competition among groups could be masked by the notions of cooperation and solidarity (Donner 2007: 671). Excessive attention is placed on the rural agrarian Third World (Robbins 2012; Walker 2006; Bebbington 2003), and on micro-scale dynamics and processes—the so-called 'local trap' (Brown and Purcell 2005: 607), although 'increasingly, the geographic situations under consideration are commonly broadened to include the global North and urban and Industrial settings' (Zimmerer and Bassett 2003: 274). While increasingly integrating qualitative/quantitative and social/natural science methods, the approach has been generally qualitative, involving in-depth case studies and ethnographies. This is inconsistent with empirical hypotheses-testing and statistical generalizability to larger populations. One solution would be more comparative and broader-scale studies that lead to 'theorizing-up from place-based studies' (Bebbington 2003: 303).

Acknowledging these critiques, we see that the specific utility of political ecology consists in providing a rich understanding of population–environment-development interactions in specific settings, characterized by contingent power relationships, local knowledge systems, and decision making by social actors. Political ecology approaches can explain the behaviors of these actors—for example, local land managers, indigenous peoples, and power-brokers—within a specific agro-ecological setting, linked through markets and other institutions to (usually unfavorable) national and global policies. This approach places most political ecology scholarship within the critical academic, post-developmental school of thought (in Table 1). The academic school has similar empirical origins with the livelihoods approach, a more practical framework widely visible in the development community.

Sustainable livelihoods framework

Taking a micro- and meso-level perspective, the sustainable livelihoods framework (SL) takes the household (within a small community, such as a village) as its core analytical unit. It examines access to different assets which can be translated by the households and communities within specific vulnerability contexts and institutional settings into different livelihood strategies (de Sherbinin et al. 2008; Aggarwal 2006, Carney 1998). Chambers and Conway (1991: 6) first defined livelihoods as 'the capabilities, assets (including both material and social resources) and activities required for a means of living'. A livelihood is regarded as 'sustainable…when it

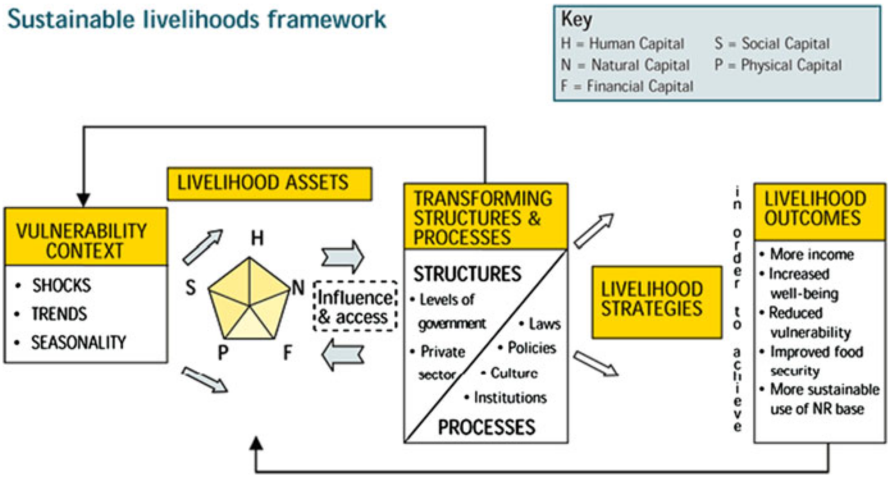

Fig. 2 Sustainable livelihoods framework. *Source*: www.livelihoodscsr.org.uk

can cope with and recover from stresses and shocks and maintain or enhance its capabilities and assets both now and in the future, while not undermining the natural resource base' (ibid.). Basically, this approach argues that we need to understand and act upon the *asset* endowments and access limitations of disadvantaged populations, the *risks* they face, and the *institutional* environment that either facilitates or blocks them in strategies to build pathways out of poverty.

Like political ecology, SL is consistent with post-developmental critiques of conventional development and is placed in row 2 in Table 1. It acknowledges power-based relations, differential access to assets and the larger 'vulnerability context' and institutional settings. It accounts for alternative value systems and ways of knowing. The normative goal is improved livelihood security.[5] The SL framework places people at the center of a web of interrelated influences that affect how these people create a livelihood for themselves and their households. The most critical element in influencing livelihoods is the assets the households have access to. It typically acknowledges five forms of capital: financial capital (inflows of money, savings), natural capital (local natural resource stocks and flows), physical capital (tools, equipment, infrastructure, built environment), human capital (access to labor, health, skills, knowledge), and social capital (networks of social support and relationships) (see Fig. 2).

The SL framework provides a lens through which to view micro- and meso-level interactions, with the *household* as a critical interface. In poor societies households often engage in multiple resource extraction activities (water, fodder, and firewood collection, cultivation, fishing) simultaneously to meet their livelihood needs. Several demographic variables at the household level—such as family size, age and sex structure, and education—are part of the asset base. Given the vulnerability

[5] The SL approach is in this way also similar to the environmental entitlements approach (Leach et al. 1999), except that institutions play the major mediating role in livelihoods related environment–society relationships in the latter approach.

context and the structures operating at the meso- and macro-level (e.g., laws, policies, culture, and institutions), households develop specific livelihood strategies. These include not only resource extraction strategies but also strategies regarding resource consumption, fertility, and migration, which then feed back into demographic and natural resources variables that determine the asset base in the next period.

Probing deeper into these links has provided rich insights into how a wide range of seemingly independent demographic and environmental processes interact and co-evolve. For instance, scholars working in this field have shown that as population grows and puts greater strain on natural resources—say in the form of depleting sources of firewood or water—households may respond by shifting to other sources or by migrating both of which dampen the pressure on local natural resource base, or by having more children which intensifies pressure in the future (Aggarwal et al. 2001; Biddlecom et al. 2005). Examining these diverse ways in which households cope with shocks to their livelihood has also helped clarifying the behavioral motivations that underpin macro-level correlations between population and environmental variables. For instance, it is often naively assumed that at the population level, increase in mortality rates due to HIV/AIDS will lower the pressure on resources due to a declining people-to-land ratio. However, empirical research has shown that increase in adult mortality rates could lead to further resource degradation if households cope with this shock through increasing their reliance on the exploitation of natural resources (Hunter et al.2005; de Sherbinin et al. 2008).

The approach has contributed significantly to a deeper understanding of the relationships between micro-demographic factors and processes and the local ecosystem, missing in earlier Malthusian type representations which ignored the diversity at the micro-level and tended to oversimplify projections from the micro- to the macro-level. It helps laying out the diversity of livelihood patterns, and consequently helps understanding the multiple intervention points and policy options available to break out of the vicious circle of poverty and environmental degradation in developing societies. Where children play an important role as providers of old-age insurance, researchers suggest that population control policy cannot be effective until alternative mechanisms for old-age security are also provided (Dasgupta, 2000). Similarly, greater tenure security, opportunities for girls' education and local health infrastructure may be more effective ways to achieve desired demographic and natural resource outcomes than focusing on family planning efforts only.

Strength of the SL framework is that it identifies assets, ways of living, and pathways out of poverty. However, it does not engage with the structural causes of vulnerability or the larger processes that lead to poverty. The updated SL framework now includes macro-level factors (see http://www.ifad.org/sla/framework/index.htm). Research based on the SL framework acknowledges the meso- and macro-level factors—such as poor markets, failed government institutions, and regressive social policies—but views them as exogenous factors affecting livelihood strategies and outcomes at the micro-level (Aggarwal 2009). A key challenges of the SL framework is thus to substantively interact and processes at the *househol*d level to the *community*, *regional*, and *global* levels. These multilevel and cross-scale interactions are more captured by system-theoretical approaches, which we turn to next.

System-theoretical approaches: CHANS, PEDA, and Supply Systems

The recursive nature of population–environment relationships has long been recognized (e.g., Gutmann et al. 1996). This perception has led to a growing prominence of system-theoretical approaches in the P–E research field. Generally, system-theoretical approaches are dedicated to the analysis of either coupled 'human–environment systems' (e.g., Turner et al. 2003), 'socio-ecological systems' (e.g., Gallopín et al. 2001) or 'social-ecological systems' (e.g., Berkes et al. 2003; Gunderson and Holling 2002; Folke 2006; Ostrom 2007). System-theoretical approaches account for dynamism, adaptive agents, and co-evolutionary processes. The paradigm shift toward embracing complexity is influencing ecological and environmental research as well as approaches to development and poverty alleviation, such as the 'dynamic systems' thinking of the STEPS Center (Leach et al. 2007; Leach et al. 2010; Scoones et al. 2007), listed as the last row in Table 1. A common feature of system-theoretical approaches in P–E research is their view of environment and population as interacting systems and a focus on the interdependence of environmental and social changes.

CHANS: Coupled Human and Natural Systems

The CHANS (coupled human and natural systems) approach seeks to provide a comprehensive framework for analyzing nature–society interactions. Coupled human and natural systems are those in which people (not just 'population') interact with natural components, for example, social-ecological systems, human–environment systems, population–environment systems, ecological–economic systems (Liu 1993; Liu et al. 1994). A particular characteristic of these systems is complexity, characterized by nonlinear relationships, feedback loops, time lags, legacy effects, thresholds, heterogeneity, and surprises (Liu et al. 2007a). CHANS research aims to reveal the underlying rules and emergent properties of these systems, and the patterns and processes that link human and natural systems. It emphasizes the potentially unpredictable effects of humans, their organizations and practices on the environment, as well as the effects of environmental changes on human populations, institutions, and behaviors. Thereby, it promotes the integration of agency and multi-scale interaction (Liu et al. 2007b: 639; McConnell et al. 2011; see also www.chans-net.org).

One example of CHANS research is on complex interactions among panda habitat, local people, and government policies in Wolong Nature Reserve in Sichuan Province, southwestern China. Wolong (200,000 ha in size) is China's 'flagship' nature reserve and one of the largest homes to the world-famous endangered giant pandas and 6000 other animal and plant species. It is within one of the 25 global biodiversity hotspots (Liu et al. 2003). There are approximately 4,500 local residents in approximately 1,200 households who conduct a variety of human activities in the reserve, such as farming (Liu et al. 1999a, b), fuelwood collection

(An et al. 2001, 2002), and tourism (He et al. 2008). The CHANS research addresses questions such as: What are the dynamics of local populations and households, panda habitat, and government policies? How do they interact with each other over time? Since the reserve's establishment in 1975, local human population size has increased by over 70% and the number of households has more than doubled. Consequently, quality habitat for the panda was dramatically reduced and fragmented (Liu et al. 2001). To prevent further degradation of panda habitat and promote habitat restoration, since 2000 the Chinese government has implemented a number of policies such as the Natural Forest Conservation Program. It provides subsidies for local residents to monitor forests from illegal harvesting (Viña et al. 2008; Liu et al. 2008). The Grain-to-Green Program offers farmers grain and cash to return their cropland on steep slopes to forests (Chen et al. 2009, 2010). As a result, the panda habitat has begun to recover (Viña et al. 2007). Using agent-based models (An et al. 2005; Chen et al. 2011) and households-based landscape models (Linderman et al. 2005), many complex attributes of CHANS were simulated. These include feedbacks among households and forest dynamics, legacy effects, surprises, nonlinear relations, and time lags (e.g., population changes had a longer time lag than changes in household numbers in terms of their impacts on panda habitat, An et al. 2005).

Central to complex systems approaches are the different types and dimensions of scale involved in human/nature interactions. Liu (2009) suggests to conduct studies at multiple organizational, spatial and temporal scales because there are not only differences between scales, but also different interactions among scales. On the one hand, many visible properties at the large-scale emerge from interactions of actors at the local scale—the concept of emergent properties of complex systems. At the same time, local interactions are often shaped by these larger (e.g., regional and global) contexts and patterns. Regarding further research, there is need to conduct more long-term studies to reveal processes and patterns that short-term studies cannot. Moreover, it would be necessary to conduct more comparative studies of different regional settings in order to produce more general principles (ibid.).

However, these general principles would require a comprehensive theoretical framework that permits integrating different disciplinary perspectives both from the natural sciences and the social sciences. By modeling complex systems, CHANS must balance the need for realism and precision with the need for generality. A triangulating approach combining multiple methods at various scales with varying emphasis on precision, realism, and generalizability could provide more robust findings than any single approach (Rosa and Dietz 2010). Another major challenge involves working on better linking the interdisciplinary CHANS framework to stakeholder needs and perceptions and engaging societal actors and practitioners in ongoing research, particularly in terms of problem formulation and identification of key processes and relationships. The fact that the CHANS research focus is to develop generalizable scientific research findings about complex dynamic systems can conflict with the need for more timely policy action in specific realms. Here, the explicit normative view of the 'dynamic sustainabilities' approach (Leach et al. 2010; Scoones et al. 2007) could complement the analytical orientation of CHANS.

It recognizes a common perception of real circumstances as dynamic, interdependent systems, and aims to develop approaches for sustainable development paths.

Population-Development-Environment (PDE) Model

One sophisticated methodology for P–E analysis was developed in the 1990 s and captures many of these features of dynamic systems: the 'PDE-model' addresses long-term relationships among population, development and the environment and aims to inform policies. This model has been adopted in various empirical case studies, and through these, has been further developed (Lutz et al. 2002b). The goal is to understand the most important factors that are likely to shape the population–environment nexus in a chosen region. Correspondingly, the studies have taken an unusually broad approach.

In order to address the issue of food insecurity in African countries, the model was enlarged to include agriculture (A) as a factor, becoming a 'PEDA model'. It links population parameters (e.g., sex/age structure, migration) to other non-demographic socio-economic variables, such as education and gender-specific labor force. All of these in turn are linked to issues such as land degradation, food production and distribution (Lutz and Scherbov 2000).

The PDE and the PEDA models have been used for a number of years in case studies covering different economic and socio-political contexts, each with specific social and ecological problem constellations, with a particular focus on 'less developed' or 'least developed' regions, such as Mauritius, Namibia, Botswana, and the Yucatán peninsula in Mexico. The dynamic models allowed researchers to combine multidisciplinary qualitative data and analyses (ethnographic, historical, anthropological studies) and interdisciplinary quantitative modeling at a meso-scale (national or sub-national). PDE/PEDA models consider changes in the population, changes in relevant parts of the natural environment, and as well as feedback loops in both directions. They further identify specific key mechanisms underlying crisis-prone developments (for a summary of case-study results and methodology see Lutz et al. 2002b).

The PEDA model is dedicated to the Human Development approach (Table 1, line 3) and is inspired by the 'vicious circle' model (VCM), which hypothesizes that a number of positive feedback loops contribute to a downward spiral of population growth, food insecurity and environmental degradation. In contrast to a Malthusian macroeconomic reasoning, however, the vicious circle model focuses on micro-economic effects at the household and community level. It provides a framework for examining fertility, poverty, low female status, and environmental degradation. The PEDA model has been further developed by the United Nations Economic Commission for Africa (ECA) as an interactive computer simulation model and is explicitly used as an advocacy tool to illustrate the likely impact of alternative policies.

The particular utility of the PDE and PEDA models for P–E research is that they address certain neglected demographic factors such as age structure and education levels. PEDA is clearly policy-oriented and seeks to help political decision makers to better understand initial conditions and to think in terms of the outcomes of alternative policy scenarios. However, in the empirical application, the PEDA model has been limited to rural societies in developing countries. In addition, the economic reasoning of the model (based on the vicious circle hypothesis) restricts it to the household level, although it could be relevant at the macro-level even if some of the assumptions remain unconfirmed and controversial (Lutz et al. 2004:190).

Social-ecological approach: Interactions of population dynamics and supply systems

The social-ecological approach was developed at the Institute for Social-Ecological Research (ISOE) in Frankfurt, Germany in the early 2000s. It relates demographic changes to the interactions between 'nature' and 'society' and follows a strong theoretical orientation (Hummel and Lux 2006; Hummel et al. 2008): Population dynamics are viewed as indicating transformations *of societal relations to nature*, that is, the relational network formed by individuals, societies, and nature in interaction (Becker et al. 2006). Using this theoretical lens, demographic changes are systematically related to the issue of provisioning the society with environmental goods, resources, and services. The point of departure is the assumption that the number of people in a given society implies regulatory requirements for supply systems resulting in social-ecological problems. However, a central normative argument is that it is not population dynamics and absolute population numbers that generate these problems, but rather the *adaptive capacity* of provisioning structures to cope with demographic changes. Given the resulting societal and scientific problems, a transdisciplinary model of supply systems has been developed for analyzing the interactions among population, nature, and society (Hummel et al. 2008; Hummel 2012). This approach is consistent with other dynamic, adaptive systems thinking and is situated in the last row of Table 1.

Provisioning structures based on ecosystems (e.g., water, food, energy) are selected so that the connections between natural resources and their utilization come to the fore. Accordingly, supply systems cover bio-physical and material-energetic dimensions (e.g., technical artifacts such as wells or bridges) as well as cultural-symbolic aspects of life (e.g., gender and social roles, needs, attitudes, cognitive orders). Given these attributes, supply systems are conceptualized as social-ecological systems (SES) and can be structured as follows (see Fig. 3):

Natural resources and their users are major components in the process of resource utilization for particular purposes. *Resources* comprise the material, organic and spatial structures that are relevant for supply systems (e.g., for food, water, or energy). *Users* are an integral part of supply systems. *Users* refer to actors and actor constellations, including producers and consumers. The users of supply systems are, however, not identical with a population; each group of users must be analyzed for a specific supply system. For instance, water-supply systems' user groups usually include individuals, households, public water utilities, industry, and agriculture. Resource utilization, however, does not involve a direct relation between users and resources. Rather it is determined by knowledge, practices, institutions, and technology. These dimensions specify how resources are made available and

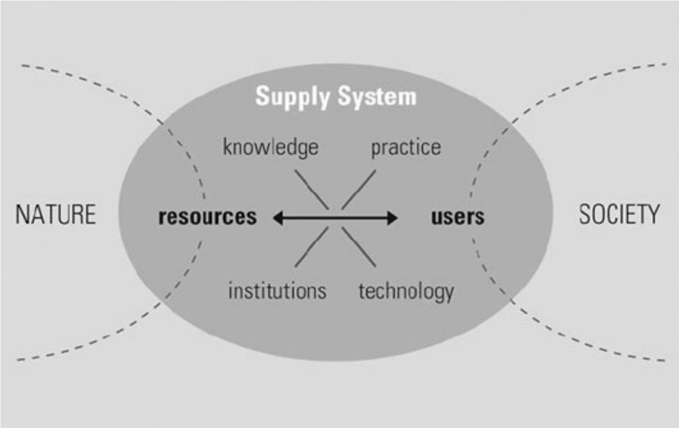

Fig. 3 Supply systems as social-ecological systems. *Source*: Hummel et al. (2008: 48)

allocated, and they determine the vulnerability, adaptability, scope and options of provisioning regulations.

The supply systems model has been applied in different case studies that covered different temporal and spatial scales and economic contexts, from sub-Saharan Africa to Europe. Each one concentrates on specific demographic aspects—migration, urbanization, population growth, and population decrease—and their implications for water or food supply systems. For example, one case study focused on the interactions among urbanization processes and food supply systems in Ghana (Janowicz 2008); another on shrinking populations and water supply in Germany (Lux 2008); a third on migration, population distribution, and integrated water resource management in Namibia (Niemann 2008), another study on population growth and water conflicts in the Middle East (Hummel 2008). This case-study approach allowed researchers to address the temporal and spatial heterogeneity of demographic changes and supply systems. In the synthesis, the model was used to identify the major challenges for the adaptive capacity of supply systems in the face of demographic changes, for example, the spatiotemporal 'misfit' between demographic dynamics (e.g., short-term migration and resulting changes in demands) and provisioning structures (e.g., persistent, centralized water infrastructure).

The supply systems model permits focusing the analysis of the interactions of population and environmental changes on the issue of provisioning and facilitates the analysis of societal utilization of ecosystems and resources. This way of posing the problem focuses on the preconditions that need to be met in order to design adaptive and sustainable supply systems. The model is further actor-oriented, since it conceptualizes any population under study as one category among other societal users of natural resources. Depending on the research question, different specifications (individuals, households, communities, consumer sectors, urban/rural, etc.) can be made. However, the generalizability of the empirical studies is limited. The conceptual model is restricted to portraying overall factors that are relevant to interactions between population dynamics and supply systems, but specific factors that might actually matter must be identified in each case, according to the mediating dimensions (knowledge, practice, institutions, and technology). For the identification of pathways to more sustainable provisioning structures and corresponding governance initiatives, a mixed methodology of surveys, participatory research and more formalized modeling would be required.

Discussion

Population–environment approaches range from revealing neo-Malthusian limits and the 'impacts' of demographic changes to complexity science and adaptive systems. Methodological approaches range from linear regression to participatory case studies from ethnographic critiques (political ecology) to simulations, and from historical case studies to scenarios of interactive human/ecological systems (e.g., CHANS, PEDA). Some approaches (e.g., political ecology or supply systems) are useful for explaining processes in a specific place, but provide little generalizability to other settings. In contrast, others offer generalizability and useful projections about the effects of a specific policy (e.g., STIRPAT), but are relatively removed from the lived experiences of people.

The following section identifies some key issues and ways forward. First, we note that 'theory matters'—i.e., social and scientific theories and normative frameworks—are relevant for understanding how to approach population–environment interactions, but this fact has not necessarily been explicitly addressed in much research. Second, we recognize that 'complexity' is becoming an acknowledged paradigm for viewing human–nature interactions and should be incorporated into population–environment-development research. Thirdly, we reflect on the preconditions of knowledge production in P–E research.

Theory matters

Some approaches to P–E relationships, such as STIRPAT, PEDA, and SL, are strongly linked to a specific, identifiable conceptual framework and development or normative orientation (Table 1); other approaches such as political ecology, CHANS, and supply systems refer to a broad, loosely affiliated school of thought with less defined parameters (such as the level of analysis) or key variables (such as demographic indicators). In each of these approaches, however, the role of scientific theories, critical social theory, and normative approaches to development and poverty alleviation have a role in guiding the variables, shaping the scale (and interactions between scales), identifying relevant stakeholders or actors, and thinking about how to link research to action.

The 'Sustainable Development' paradigm of the 1980s is allied with linear and multiplicative perspectives and mediating perspectives. This leads to a focus on administrative units (countries, urban areas, variables such as markets and prices) and formal policies. Recommendations tend to focus on capturing externalities in a given system, and on population as a driver and target for policy action, to the exclusion of power, politics, and inequality and interactions at different scales. The rise of 'Critical Post-Developmental Thought' is allied to critiques of development and the search for alternatives to development. This school is consistent with critical P–E research in the political ecology school of thought and privileges small-scale, local actions and research. This school of thought has limited relevance for altering national and global policy frameworks, however. The 'Human Development' paradigm became the dominant normative development paradigm in the 1990s and is thus broadly consistent with a range of mediated models, SL approach, political ecology as well as with systems-feedback models, but provides no guidance on relevant ecological systems or demographic variables. These models are all useful for capturing aspects of interacting systems at different scales, and for engaging with actors from the household to the government and international authorities. The recent turn to viewing development as a process of opening up 'pathways to sustainability' (Leach et al. 2007) recognizes the widespread paradigm shift to non-equilibrium systems thinking and complex adaptive systems. This captures a normative, epistemological, and policy shift, which subsumes CHANS and the supply systems approach, as well as SL approach, political ecology and mediated models.

Given these underlying implicit or explicit notions of development, the way of posing the problem differs (e.g., as one of population numbers with specific impacts, or of power relationships that can be negotiated and change). STIRPAT, linked to 'mainstream sustainable development', is grounded in a classical division between science (an objective form of knowledge) and society (policy acting on behalf of the people). It aims at providing preferably objective and robust knowledge which can then rationally inform policy. In contrast, political ecology professes a normative orientation toward social justice and acknowledges agency, power relations, and exclusion—with an eye toward social change. The supply systems approach emphasizes the normative goal of sustainable provisioning structures serving human populations, recognizing that needs can vary and require public debate. Thus, diverse theories around P–E lead to different problem depictions, research questions, conclusions, and notions of policy relevance. There is no blueprint approach that works in all settings.

Complexity

Zaba and Clarke (1994: 36) had already affirmed many years ago that 'the field of population and environment interactions (…) is itself complex and diverse, capable of study at various levels, from the local to the global, and from various viewpoints: from the demographic, social and economic, the geographical, ecological and environmental'. There is a strong consensus in P–E analysis that population dynamics affect social, cultural, political, economic and ecological development, with demographic processes in turn being influenced by social, cultural, economic and ecological conditions, that is, recursive causal relations are at work. Furthermore, there are critical temporal and spatial dimensions, that is, variations in time and space of the elements and interactions, which introduce aspects of historical processes, context, geographic and temporal scale, and hierarchy (Adamo 2007). Thus, models are needed which can map the important connections in this nonlinear, interdependent network of causality and co-evolutionary processes.

One common characteristic of the contemporary approaches is their recognition of some aspects of complexity, the relevance of scale and dynamic systems. The conceptual approaches are applicable to different spatial scales: STIRPAT, for example, is usually applied at the macro-scale, while SL usually refers to the micro-scale and the supply systems approach to the meso-scale. It is important to recognize the difference that scale makes and to look at cross-scale interactions. Furthermore, key variables and their interactions must be identified. Thereby different theories lend themselves to identifying different key variables and paths of interaction.

On the other hand, complexity is frequently proclaimed at the cost of more useful simplicity of interpretation and communicability to non-scientific actors. An integrated analysis of population, environment and sustainability needs to reduce the complexity in the real world—in a way that clearly represents the significant interactions among social and ecological processes and their outcomes (Glaser et al. 2012). Elinor Ostrom (2007, 2009) has presented a general framework for analyzing the sustainability of social-ecological systems. Population growth or density are not foregrounded as key variables, but are part of the social, economic and political setting (and indirectly as the number of resource users). This framework could be helpful for linking across different theories discussed here to provide a framework for comparative studies.

New forms of knowledge production: toward trans-disciplinary approaches

Given this trend toward complexity, one way forward is to engage in research that reflects on preconditions of knowledge production, going beyond interdisciplinary thinking to transdisciplinary scholarship. Research that transcends the boundaries of natural-scientific and social-scientific disciplines is reflected in calls for ‘interdisciplinarity’. We argue that research is also needed that includes the values and historical knowledge of societal actors as constitutive elements of the research process—reflected in the notion of transdisciplinarity (Gibbons et al. 1994; Hirsch Hadorn et al. 2008; Bunders et al. 2010). Transdisciplinarity calls for viewing research as a mutual learning process involving both science and society. It is not the exclusive domain of scientific experts who translate their findings to a lay public or policy makers.

Some approaches reviewed here—political ecology, livelihoods, supply systems and dynamic systems—are working in this direction. They explicitly incorporate non-scientific knowledge. These approaches harness both forms of knowledge for projects that involve cooperation with development agencies and other stakeholders. However, promoting transdisciplinarity in P–E research requires substantial institutional change within the academia and research establishment (Thompson-Klein et al. 2001). The challenge for academic institutions is to train future researchers and offer incentives to overcome the limits of conventional disciplines, for example, by providing inter- and transdisciplinary study programs.[6] Moreover, transdisciplinary research requires particular methods and tools that facilitate the integration of divergent concepts and problem perceptions and that allow to link scientific knowledge and practical knowledge in a rigorous manner. Here, P–E studies could learn from the growing body of methodologies developed in sustainability sciences (Thompson-Klein et al. 2001; Pohl and Hirsch Hadorn 2007; Jahn 2008; Bergmann and Schramm 2008; see also STEPS centre http://www.steps-centre.org).

Conclusion

There exist no theoretical and methodological panaceas as far as P–E interactions are concerned. Different conceptual approaches are not mutually exclusive, but can instead be combined and complement each other. Choice of a P–E model should depend on: a) the objective of study participants—researchers and societal stakeholders, b) how the problem at hand demands attention to scale and interactions and a wide range of social, demographic and ecological dynamics, and c) the need to communicate potentially complex system patterns to policy makers or societal stakeholders seeking simpler, identifiable points of intervention. Thus, a combination of approaches and methods (e.g., the quantitative and more qualitative methods) could be productive.

Core issues for future research emerged from the PERN 2009 seminar: First, more long-term studies of human–environment processes are needed, since P–E processes take place over longer periods of time. Second, more comparative studies are needed, operating at different temporal, spatial, and social scales. A common framework can help us conduct comparable studies. This could include meta-analysis of the existing case studies to distill the key multi-level processes and cross-scale interactions. Finally, we should seek to offer lessons to policy makers and practitioners that go beyond 'one-size-fits-all' blueprints solutions. Instead, we should expect more nuanced and context specific, yet pragmatic interventions that help us understand and address significant and diverse population–environment problems the world faces in this century.

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[6] So far, several universities offer such programs in the area of 'sustainability science' or non-disciplinary programs (i.e., IDS, Stockholm/Sweden; Leuphana University, Lueneburg/Germany; ASU School of Sustainability/USA).

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