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# Assessing sustainable biophysical human–nature connectedness at regional scales

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## Abstract

Humans are biophysically connected to the biosphere through the flows of materials and energy appropriated from ecosystems. While this connection is fundamental for human well-being, many modern societies have—for better or worse—disconnected themselves from the natural productivity of their immediate regional environment. In this paper, we conceptualize the biophysical human–nature connectedness of land use systems at regional scales. We distinguish two mechanisms by which primordial connectedness of people to regional ecosystems has been circumvented via the use of external inputs. First, 'biospheric disconnection' refers to people drawing on non-renewable minerals from outside the biosphere (e.g. fossils, metals and other minerals). Second, 'spatial disconnection' arises from the imports and exports of biomass products and imported mineral resources used to extract and process ecological goods. Both mechanisms allow for greater regional resource use than would be possible otherwise, but both pose challenges for sustainability, for example, through waste generation, depletion of non-renewable resources and environmental burden shifting to distant regions. In contrast, biophysically reconnected land use systems may provide renewed opportunities for inhabitants to develop an awareness of their impacts and fundamental reliance on ecosystems. To better understand the causes, consequences, and possible remedies related to biophysical disconnectedness, new quantitative methods to assess the extent of regional biophysical human-nature connectedness are needed. To this end, we propose a new methodological framework that can be applied to assess biophysical human–nature connectedness in any region of the world.

## 1. Introduction

Human societies are inherently connected to and dependent on the biosphere and its functions (Boulding 1966, Daily 1997, Folke *et al* 2011) through the flow of materials and energy (Haberl *et al* 2014, Cooke *et al* 2016). However, modern societies have increasingly disconnected themselves from their immediate regional environment by accessing material and energy flows from distant places (Kastner *et al* 2014, Bergmann and Holmberg 2016) and from outside the biosphere (Wiedmann *et al* 2015). Industry, technology and long-distance trade have enabled a disconnect of human activities from the primary production of their regional environment (Yu *et al* 2013), and from the biosphere by relying on industrial mineral resources (i.e. fossils, metals, and other minerals extracted from the lithosphere (Cumming *et al* 2014)). Hence, despite growing calls for societal reconnection to the biosphere (Folke *et al* 2011, Andersson *et al* 2014, Folke *et al* 2016), what this means from a biophysical perspective remains poorly understood.

The notion of biophysical human–nature connectedness is in conflict with the notion of decoupling socio-economic activities from natural resource use. In parallel to growing calls to 'reconnect' to the biosphere, other scholars have noted a relative decoupling of material throughput and economic growth for some regions (e.g. Fischer-Kowalski and Swilling 2011). Nevertheless, the economy is embedded in the environment (Martínez-Alier and

Muradian 2015, Folke *et al* 2016), all resources used in the economy are drawn from the environment, and all waste must return to the environment. Therefore, complete and sustained decoupling of economic activities from the environment is, by definition, untenable. Moreover, Cumming *et al* (2014) argued that a disconnect weakens direct feedbacks between ecosystems and societies, thereby potentially causing overexploitation and collapse. Others have claimed that disconnections provide opportunities for wild nature to be sustained by decoupling human development from environmental impacts (e.g. Asafu-Adjaye *et al* 2015). The purported benefits of purposeful disconnection are premised on intensified, more efficient land use. However, there is considerable debate regarding the efficacy and sustainability of such moves (Loos *et al* 2014a). For example, human–nature disconnectedness can increase inter- and intragenerational injustice by taxing future generations and distant regions (Haberl *et al* 2002, Martinez-Alier *et al* 2014) via overconsumption, depletion of natural resources, and pollution of the environment (Pearson 2007, Wiedmann 2016). In addition, disconnection from the natural environment may foster a systemic cognitive distancing of land use related activities from their environmental impacts (Cumming *et al* 2014, Seppelt and Cumming 2016).

Both perspectives—increasing or decreasing our distance to nature—share the goal of reducing pressure on ecosystems, but with different underpinning assumptions. By increasing our distance to nature we pin our hopes on the 'efficiency' of industrial technology in order to 'spare' land (Waggoner 1996)—a core idea of ecomodernism (Asafu-Adjaye *et al* 2015). We argue that this view fails to recognize spillover and distal effects, and is largely blind to issues of justice. For this reason, we instead argue for a reconnection of human activities to the biosphere and its regenerative cycles. This, in turn, implies not only a reduction of industrial material use and a limitation of human domination of ecosystems, but also a strengthened sense of being connected with and knowing the limits of nature (Folke *et al* 2011).

To facilitate constructive debate on whether we should reconnect to or disconnect from the biosphere, in this paper, we propose a conceptual framework to analyze regional-scale biophysical human–nature connectedness. The proposed framework builds on the regional land use system as unit of analysis. Yet it explicitly recognizes not only regional land use, but also global material trade and energy flows. By accounting for both economic and biophysical processes, we integrate concepts such as self-sufficiency, land use intensity, resource use, biophysical and embodied trade flows, waste generation, and environmental feedback loops into the framework. Thus, the framework provides a new lens through which land use sustainability can be investigated, which goes beyond 'on site' efficiency thinking (Fischer *et al* 2014, von Wehrden *et al* 2014). Our focus in this paper is primarily conceptual, but we also provide an outlook for how existing methodological approaches can be used to operationalize the proposed framework.

The paper is structured as follows. First, we outline our conceptual model, distinguishing between different types of biophysical disconnection. Second, we provide concrete examples to illustrate how the proposed framework can help to understand the sustainability challenges facing different regions. Finally, we provide a methodological outlook showing avenues how the proposed framework can be operationalized in order to generate quantitatively robust measures of regional-scale biophysical human–nature connectedness.

## 2. Conceptualizing regional biophysical human–nature connectedness

Regional land use systems are an appropriate unit to analyze biophysical human–nature connectedness because (1) energy and material flows across larger extents are typically too heterogeneous to be usefully aggregated; and (2) humans meaningfully experience life at regional scales (Kissinger and Rees 2010, Wu 2013). The spatial boundary of a 'region' will most often be defined by sub-national political-administrative units (e.g. from municipalities to federal states), as this is a vital scale for many political decisions (Dearing *et al* 2014) and usually the finest scale at which relevant material and energy flow data is available.

There are multiple ways in which humans' connectedness to natural ecological productivity can be conceptualized. For example, Seppelt *et al* (2014) suggest a framework based on distinguishing between renewable and non-renewable resource use. However, for regional assessments clear system boundaries are required, therefore, our framework distinguishes between two realms of land use related disconnectedness from the regional biosphere. The first possible realm is 'biospheric disconnectedness', and stems from the use of materials external to the biosphere, such as artificial agrochemicals, fossils or machinery. The second possible realm is 'spatial disconnectedness', and relates to the appropriation of distal ecological goods to bolster local production via imports of biomass, including food, timber, or feed for livestock. Moreover, one could consider the import of mineral resources used to extract and process ecological goods in the region as an additional form of spatial disconnect.

Both biospheric and spatial disconnectedness have potentially far reaching consequences for sustainability. Biospheric disconnection is characterized by a strong dependence on industrial inputs which delay or displace ecological constraints (Norgaard 1988, Martinez-Alier *et al* 2014). This raises concerns about intergenerational justice, because it creates societal structures that cannot be maintained indefinitely, and diminishes the biosphere's life-supporting conditions for future generations (e.g. through causing climate change). Similarly, spatial disconnection can result in the net appropriation of resources which create unsustainable lifestyle patterns (Brand and Wissen 2012, 2013) through teleconnections (Tukker *et al* 2014, Wiedmann *et al* 2015) that potentially disadvantage the 'source' regions. Spatial disconnectedness may thus compromise intragenerational justice, especially if the teleconnections are strong and unbalanced (Dorninger and Eisenmenger 2016, Teixidó-Figueras *et al* 2016).

### 2.1. Intraregional connectedness

Before considering the effects of biospheric and spatial disconnectedness in detail, it is necessary to develop a regional baseline for comparison. To this end, we first define *intraregional connectedness* as comprising the extent to which humans appropriate net primary production (NPP) for their own purposes, in combination with the labor used to appropriate this energy. A balance is required between regionally self-sufficient use of (ecologically derived) material and energy by humans and the availability of such flows to other species. The extent to which humans appropriate the NPP of the terrestrial ecosystems and the amount of trophic energy remaining in the ecosystems for other species indicates the level to which humans directly interact with, and source energy and materials from, ecosystems. In practice, intraregional connectedness may be measured via estimates of human appropriation of net primary production (HANPP) (Imhoff *et al* 2004, Haberl *et al* 2007b) and the labor inputs required to appropriate the NPP.

Direct human and animal labor in land use activities must be considered in the assessment of intraregional connectedness for several reasons. First, labor input is an important factor in the appropriation of net primary production: A system where net primary production is appropriated mainly by human and animal labor is likely to have very different sustainability outcomes than one where the appropriation is largely enabled by fossil fuel usage, even if the two systems have similar levels of HANPP. Second, direct labor is a form of internal input as long as working people and animals are 'fueled' by regional biomass products (Tello *et al* 2016). Third, from a human–nature connectedness perspective direct labor input in land use activities fosters rather than decreases biophysical and cognitive human–nature relationships (Cumming *et al* 2014, Webber *et al* 2015, Soga and Gaston 2016).

### 2.2. Biospheric disconnectedness

The relevant systems boundary for identifying *biospheric disconnectedness* is formed by the biosphere—the sphere of Earth where living organisms are found (Allaby 2008)—excluding, for example, the lithosphere, where minerals are sourced from. Thus, all mineral and non-renewable material and energy flows, no matter if they were sourced from inside or outside the spatial boundaries of the region, are considered as non-internal flows. However, considering the increase in global trade flows it is still useful to differentiate between regionally sourced and imported minerals that are used for land use related activities, i.e. the production, extraction and processing of ecological goods. In fact, minerals imported for land use related activities create both biospheric and spatial disconnection (see section 2.3 and figure 1).

The degree of biospheric disconnectedness is determined by (1) the direct and embodied flows of mineral inputs (in the form of agrochemicals, fossil fuels, or materials embodied in machinery) that are drawn from outside the biosphere; and (2) waste flows and emissions caused by the use of such inputs (e.g. greenhouse gas emissions). To grasp the full extent of material and energy requirements within the land use system, it is necessary to account not only for direct non-biospheric inflows, for example, the use of fossil fuel based artificial fertilizers, but also for indirect flows, for example, the energy, material, and labor inputs which were necessary to build an agricultural vehicle or the energy required for producing chemical fertilizers (see table 1).

Intensified agricultural practices from the 1950s onwards have led to increased yields (Pimentel *et al* 1973, Pimentel 2009, Martinez-Alier 2011). However, this short-term boost of regional net primary production (NPP) is typically driven by phosphorus, nitrogen and fossil fuels drawn from outside the biosphere (Erb *et al* 2012, Niedertscheider *et al* 2016). The exhaustion of non-renewable materials and the associated production of wastes and pollution during the use of such resources cause serious sustainability problems (Daly 1990). Addressing the 'displaced' impacts of those problems (Haberl *et al* 2002) both temporally (e.g. resource depletion, climate change) and spatially (trade related environmental burden shifting to distant regions), is particularly problematic without a detailed understanding of the non-biospheric energy and material flows that cause them.

### 2.3. Spatial disconnectedness

Regional land use systems are increasingly connected to distal regions via global markets (MacDonald 2013, Henders *et al* 2015, Chaudhary and Kastner 2016). It is, therefore, vital to include and identify interregional exchange relationships in any framework that describes biophysical connectedness. Trade flows of crops and other biomass commodities create biophysical connections to distant places, increasing the disconnect from the regional natural productivity (NPP) (Krausmann *et al* 2008, Mayer *et al* 2015). We define biological resources drawn from within the defined regional boundaries as internal flows, and consequently understand all other biological resources

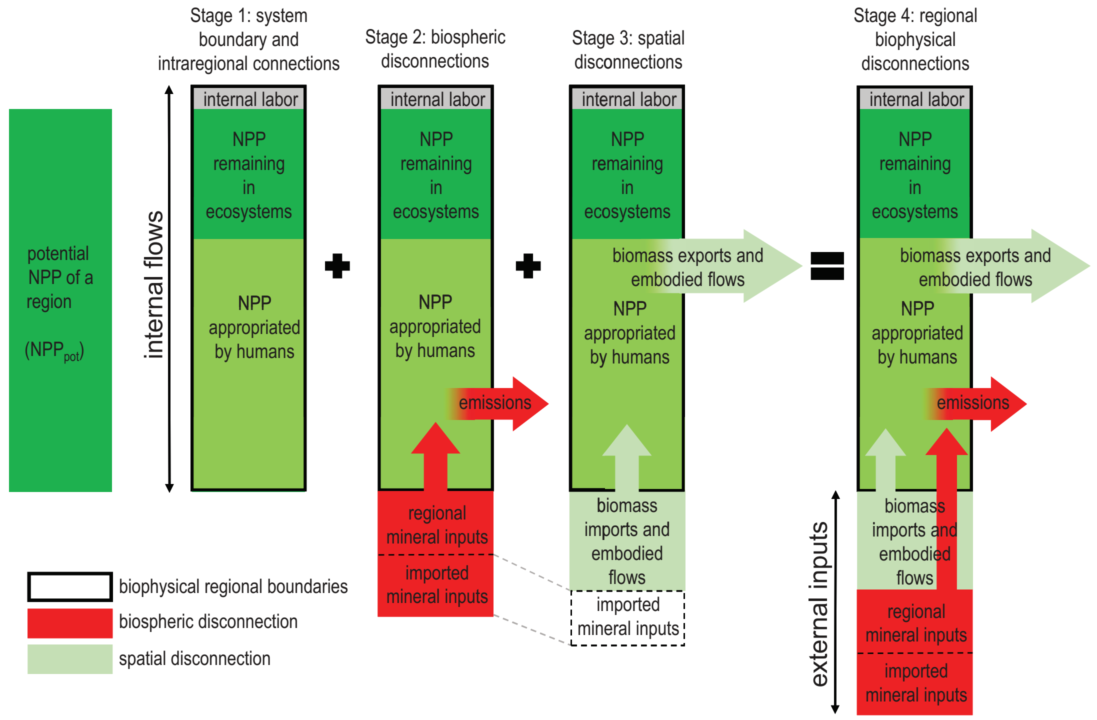


**Figure 1.** Conceptual steps towards assessing levels of biophysical human–nature connectedness and disconnections. From left to the right: the first bar shows the potential net primary production of a specific region ($NPP_{pot}$). Stage 1 indicates the fraction of the NPP appropriated by humans and what remains in the ecosystems for other species. Stage 2 shows biospheric disconnection by means of extra-biospheric inputs and emissions, whereby it is important to differentiate between regionally sourced and imported mineral inputs as indicated by the dotted line. Stage 3 shows spatial disconnections caused by intraregional biomass imports and exports. As indicated by the dashed area at the bottom, imported minerals can additionally be considered as causing spatial disconnectedness. Applying both aspects of disconnectedness to the intraregional connectedness results in the full assessment of biophysical human-nature disconnectedness at regional scales (Stage 4).

**Table 1.** External inputs into the land use system (Pimentel *et al* 1973 2008, Tello *et al* 2016). The left column lists material and energy inputs that enter the land use system from outside the biosphere and cause biospheric disconnectedness. These inputs may either come from regional sourcing or imports. The right column includes relevant intraregional trade of biomass based commodities which cause spatial disconnectedness.

| *External inputs* | |
|---|---|
| Industrial mineral inputs (differentiated by regional sourcing or imports) | Biomass imports |
| - Machinery use | - Embodied HANPP flows (section 4) of: |
| - Associated fossil fuels for machinery | • Livestock feed |
| - Agrochemicals (e.g. artificial fertilizers, pesticides) | • Food |
| - Irrigation and water pump facilities | • Fiber and timber for textiles and construction |
| - Industrial seed production | • Livestock |
| - Embodied flows of materials, energy, and labor for the production of all that items | • Biomass for bioenergy purposes |
| | - Embodied flows of materials, energy, and labor in all that commodities |

flowing into the region as 'external inputs' (table 1). *Spatial disconnectedness* can therefore be quantified via the amount of biomass based commodities imported to and exported from a region. Moreover, the import of minerals for land use related activities can be considered as an additional form of spatial disconnection. In order to reveal the full extent of disconnectedness, the embodied flows of material and energy associated with those biomass based imports and exports should also be accounted for.

Here it is important to note that trade-enabled material and energy exchanges between regions do not per se compromise sustainability. Some studies stress the economic and ecological efficiency gains that arise from free trade and long distance relationships (Bhagwati 2007, Martinez-Melendez and Bennett 2016). Other scholars observe asymmetric power relationships and systematic inequalities in 'ecologically unequal exchange' relationships (Hornborg and Jorgenson 2013, Dorninger and Hornborg 2015) which provide only the pretense of efficiency and decoupling gains (Weinzettel *et al* 2013, Wiedmann *et al* 2015, Bergmann and Holmberg 2016). Regardless of the contention regarding the benefits of such land use related trades, we can say that distal trade relations always cause spatial human–nature disconnections.

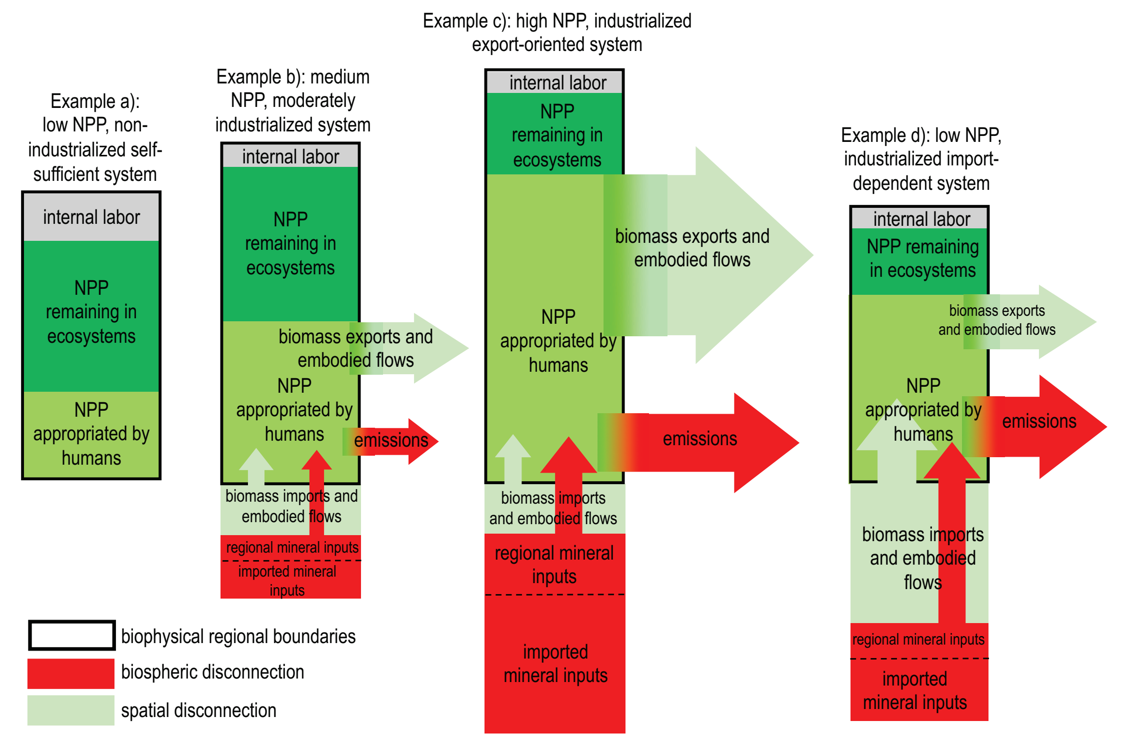


**Figure 2.** Four exemplary regional land use systems illustrating regional connectedness and different degrees of biophysical disconnectedness respectively. The four examples exhibit varying levels of potential NPP ($NPP_{pot}$). Example (*a*) represents a system that does not access non-renewable or distant goods, meaning that human-induced energy inputs only come from labor. Example (*b*) draws on resources from both outside the region and outside the biosphere, which allows internal labor input to decrease significantly. Example (*c*) heavily relies on mineral inputs in order to produce commodities for exportation. Additionally, major parts of NPP are appropriated and emissions released. Example (*d*) shows largely human controlled regional ecosystems, which uses considerable shares of the available NPP and additionally heavily draws on external inputs which are mostly being imported.

These distal relations, or 'teleconnections' (Adger *et al* 2009, Haberl *et al* 2009, Yu *et al* 2013), not only involve long distance transportation (Cristea *et al* 2013) and environmental load displacement (Peters *et al* 2011, Peng *et al* 2016), but crucially also the substitution of regionally available biospheric resources by distal ones. This increases the complexity of the environmental and societal impacts arising from a given land use and cognitive and psychological disconnectedness from the environment (Kissinger and Rees 2010).

Figure 1 shows the conceptual steps towards assessing the levels of biophysical human–nature connectedness and potential disconnections.

## 3. Archetypical examples

We illustrate our conceptual framework for different regional land use systems with four archetypal systems. For each of the four systems the height of each component indicates the relevant throughput of energy and materials related to intraregional connectedness, spatial and biospheric disconnections (figure 2). A self-sufficient, non-industrialized, subsistence system which does not use any non-renewables in their land use practices, but relies solely on biomass goods and on relatively high labor input, has neither spatial nor biospheric disconnections (figure 2(*a*)). Such systems represent subsistence farming regions which were common especially before the 20th century in most parts of the world (Krausmann 2001, Erb *et al* 2008). Moderately industrialized systems exhibit moderate levels of external inputs which allow a comparatively higher NPP appropriation with significant lower labor input (figure 2(*b*)). Such systems may include regions in transition from an agrarian to a more industrial society, for example, regions of Eastern Europe (Hanspach *et al* 2014, Loos *et al* 2014b). In contrast, a strongly exported oriented, highly industrialized system with high NPP availability is both spatially and biospherically more disconnected (figure 2(*c*)), for example, export-oriented soybean production regions in Brazil (Wittman *et al* 2016). Finally, an industrialized system with a high HANPP and high external inputs indicates strong regional disconnection and both temporal and spatial displacement of environmental burdens (figure 2(*d*)). Similar systems are likely to be found in densely populated, largely urbanized and wealthy regions such as Western Europe (Niedertscheider *et al* 2014).

Regions where direct labor input has largely been displaced by external inputs may exhibit a similar HANPP, but differ greatly with regard to the other two dimensions—biospheric and spatial disconnection (figures 2(*b*) and (*d*)), this has far reaching sustainability outcomes not only for the focal regions, but also for the distant regions they are connected to. Identifying the nature and extent of such regional disconnections is a crucial first step in addressing the

**Table 2.** Methods register and key references. The left column lists the methods to quantify regional biophysical human–nature connectedness. The relevant key references for each approach are provided in the right column. The ideal units of measurement are given in square brackets (where applicable), where [t] stands for metric tons, [J] for joules, and [h] for hours.

| Methods and models of environmental accounting | Key references |
|---|---|
| Human appropriation of net primary production (HANPP) [t] [J] | • Vitousek *et al* 1986, Haberl *et al* 2007a |
| Material and energy flow analysis (MEFA) [t] [J] | • Haberl *et al* 2004, Fischer-Kowalski and Haberl 2007 |
| Accounting of embodied flows | |
| • environmentally extended input output analysis (EEIOA) | • Leontief 1970, Kitzes 2013 |
| • extension factors | • Pimentel *et al* 2008, Kastner *et al* 2015 |
| Types of embodied flows | |
| • embodied HANPP (eHANPP) [t] [J] | • Erb *et al* 2009, Haberl *et al* 2009 |
| • raw material equivalents [t] [J] | • Schaffartzik *et al* 2015b, Eisenmenger *et al* 2016 |
| • embodied labor [J] [h] | • Alsamawi *et al* 2014, Simas *et al* 2015 |
| • embodied energy [J] | • Agostinho and Siche 2014, Aguilera *et al* 2015 |

cross-scale sustainability challenges related to such interconnected systems. Without genuine reconnectedness, humans are only at best peripherally aware of the full range of impacts their lifestyle has on other and future generations, and on other species. A more complete understanding of human–nature connectedness and opportunities to reconnect, might increase the leverage potential of actions set in land use systems towards transformational change (Meadows 1999, Abson *et al* 2016). It is to be hoped for that biophysically reconnected regional land use systems ultimately promote a more foresightful, responsible and conscious society, based on a living with rather than dominating nature.

In regionally connected land use systems, largely reliant on (transformed) solar energy and labor as major energy inputs, in- and outputs will then be reconnected to the natural cycles—the regeneration and uptake rate—of the biosphere (Folke *et al* 2016). A reconnected land use system will strengthen self-sufficiency, circularity in production and consumption; involve less teleconnections, less specialization, more diverse land uses, and relations of trust (Tregear 2011, Weatherell *et al* 2003). Here the major balancing challenge is ensuring that sufficient biospheric resources are appropriated for human well-being while retaining resources available for the flourishing of other species.

In all cases the assessment of regional biophysical connectivity, particularly if linked to other regional indicators, can help identify regionally specific challenges in transitioning towards more sustainable land use systems. In addition, multi-scalar assessments may help identify 'natural' scales of biophysical connectedness and appropriate scales for managing material and energy flows.

## 4. From theory to practice: methodological guidelines

In this section we present methodological guidance to operationalize our concept of biophysical human–nature connectedness at regional scales. Building on well-established methods (table 2) this operationalization will allow assessment of the extent to which systems are built on and driven by intraregional connectedness and biospheric and spatial disconnectedness respectively (figure 3).

As discussed above, we consider HANPP as an appropriate starting point to quantify intraregional connectedness. HANPP is based on not only appropriated biomass yields from farming, grazing, and forestry, but also harvest related losses, unused biomass extraction, conversion losses, and land use conversion—changes in the HANPP fraction due to indirect changes to NPP. A land use conversion effect can only be quantified in relation to the potential net primary production ($NPP_{pot}$) that would occur at a certain area without any human interference. A range of different models exist that allow for a computation of site-specific photosynthesis performance (Haberl *et al* 2014). For example, the Miami model (Lieth 1975) calculates $NPP_{pot}$ from average precipitation and annual mean temperature of an area. Other models additionally include information on soil texture, latitude, and $CO_2$ availability (Sitch *et al* 2003). By subtracting the HANPP, i.e. all harvest and related flows plus the land use conversion, from the $NPP_{pot}$, one arrives at the NPP that remained in the ecosystem after harvest and which is available for other species ($NPP_{eco}$) (Krausmann *et al* 2013, Plutzar *et al* 2015). By going beyond simple harvest or yield assessments HANPP reveals the connectedness to the productivity, and the potentially renewable resources, of ecosystems.

From an ecological perspective, low HANPP may be a desirable goal because it leaves a large amount of energy to other species (Haberl *et al* 2007a). In contrast, if low HANPP values are achieved via the use of non-renewable resources or distant biomass the overall outcomes for sustainability may still be negative (with regards to future generations and distant regions). However, as the conventional HANPP method neither captures external inputs, such as the materials and substances that are used to

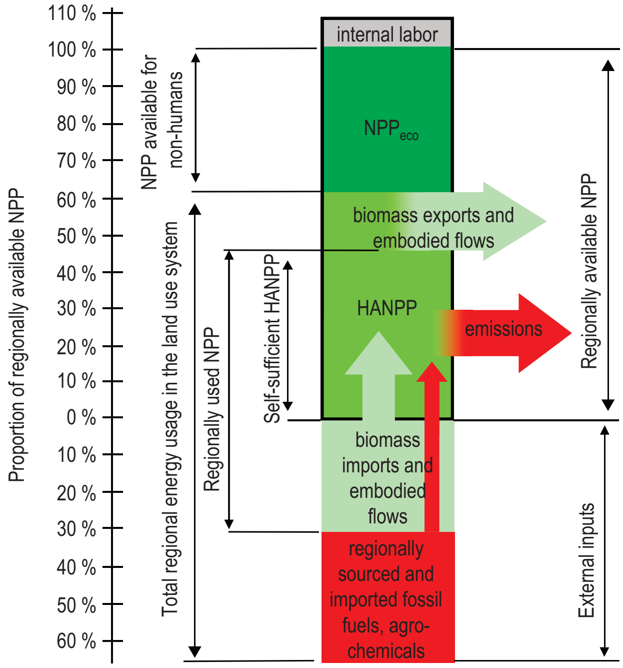


**Figure 3.** The parts of biophysical human–nature connectedness framework that need to be quantified. NPP$_{eco}$ shows how much trophic energy is available for non-human species after harvest. Internal labor input and HANPP are both influenced by the extent of external inputs and biomass imports. Outflows of the system are exports of biological resources, their embodied flows and emissions to air, water, and land. All components constituting the intraregional connectedness, internal labor input, NPP$_{eco}$, and HANPP, as well as the external inputs, traded biomass and mineral inputs, can all be expressed in terms of energy [J]. Thus, they can be given as proportions of the regionally available NPP. Only emissions and generated wastes cannot be directly expressed in terms of energy.

produce and harvest goods in the land use system (Haas and Krausmann 2015), nor trade related teleconnections (Haberl *et al* 2009, Kastner *et al* 2015), nor the labor inputs to those systems, further methodological steps are required to evaluate regional scale biophysical human–nature connectedness.

Biospheric disconnections can be assessed via a social–metabolic analysis of the regional land use system. Social metabolism quantifies, similar to the metabolism of organisms, the biophysical inputs and outputs of a social–ecological entity. It is operationalized by material and energy flow accounting analysis (MEFA) (Fischer-Kowalski and Haberl 2007). While analysis of socio-ecological energy and material flows is well established, particularly at the national level (Fischer-Kowalski *et al* 2011, Haberl *et al* 2004), the notion and consequences of changes to 'regional biophysical human–nature disconnections' is hardly explored in that literature. However, by conducting such a MEFA analysis one is able to calculate the throughput of materials and energy of the land use system and subsequently relate these flows to regional and cross-scalar sustainability challenges.

The system boundaries of the adopted MEFA analysis are defined by the spatial boundaries of the region (Sastre *et al* 2015) and the boundaries of the biosphere. In order to account for differing levels of teleconnectedness, it is important to differentiate between regionally sourced mineral inputs and imported ones. Doing so can help reveal related additional transport costs, patterns of ecologically unequal exchange and outsourcing of material and energy intensive processes. Industrial mineral inputs, such as machinery use, fuels, or agrochemicals, enter the system from outside the biosphere (left column of table 1) and potentially from outside the region. Outflows are those materials and substances that are not reused in the land use system but create pollution, wastes, and emissions.

Artificial fertilizer, seeds and machinery production processes are an energy and material intensive endeavor (Pimentel *et al* 2008). In order to reveal the full extent of energy, materials and labor required for the external industrial inputs into the land use system, the embodied flows of those inputs must be accounted for. We suggest using either product and region specific extension factors (Kastner *et al* 2015, Schaffartzik *et al* 2015a), or regionally adjusted environmentally-extended input-output analysis (EEIOA) (Miller and Blair 2009, Kitzes 2013, Schaffartzik *et al* 2014) where intersectoral linkages can be retraced, i.e. the flows between the land use sector and other socio-economic sectors of the region.

The third and last methodological measure of the framework is to collect data on the biomass based interregionally traded goods for quantifying the spatial disconnect. In short, all directly traded biomass commodities (table 1) such as crops, animal products, textiles, other fibers, bioenergy products, and wood products, and the indirect flows of NPP, materials, energy, and labor embodied in these goods need to be captured. The latter are usually not reported in trade statistics. Still, the methodological goal is to redistribute the flows embodied in the goods from the place of origin to the place of final consumption (Kastner *et al* 2015, Wiedmann 2016).

To comprehensively reveal the biophysical processes necessary to produce a specific commodity and to disclose how the consumption of traded goods affects connectedness an environmentally-extended input-output table or extension factors, which are adjusted for the specific region and year, would potentially provide the best systematic approach to assess the embodied flows of traded products. The results of embodied HANPP (Erb *et al* 2009), raw material equivalents (Schaffartzik *et al* 2015b, Eisenmenger *et al* 2016), embodied energy (Agostinho and Siche 2014, Perryman and Schramski 2015), or embodied labor (Alsamawi *et al* 2014, Simas *et al* 2015) are established indicators, increasingly used in the scientific literature to reveal international inequalities and related environmental pressures (Teixidó-Figueras *et al* 2016).

Different types of flows have different metrics: NPP and HANPP can be expressed in terms of dry matter [t], carbon [t] or energy units [J]; labor input in time units [h] or energy [J]; materials in units of mass [t] or enthalpy [J]; emissions in GHG potentials [t $CO_2$ equivalents] and nitrogen leaching [$NO_3$]. For achieving comparability between regions we suggest to evaluate connectedness on a per unit area, or per capita basis; comparability within regions may be achieved via an expression of flows in energy units (except emissions), i.e. flows of HANPP, material, and labor. The final result of the framework provides a measure of the degree to which a regional land use system is biophysically connected to the productivity of the regional ecosystems (NPP) and disconnected in terms of external inputs (figure 3).

The empirical application of this framework will likely involve challenges with regards to data availability and the computation of critical embodied flows. In particular, identification and assessment of interregional trade flows from material accounting data will involve region-specific difficulties. For example, physical trade relations between regions might not be reported by authorities. Therefore, we encourage consultation of relevant stakeholders to assure the validity of data where necessary. Likewise, the calculation of embodied flows is a sensitive methodological endeavor (Schaffartzik *et al* 2015b). It will therefore be important to provide detailed information on steps of the decisions that have been made regarding data sources and estimations to ensure transparency and traceability.

## 5. Outlook

We argue that the regional land use system is an appropriate unit of analysis for investigating biophysical connectedness as it provides a focal unit for understanding cross scale interactions between land use systems, revealing key environmental feedback loops in and between regions. We recognize that we take a relatively pragmatic definition of 'region'. Yet, in principle it should be possible to use this approach to identify spatial extents within which there are high levels of connectedness or across which significant disconnections occur.

Biophysical human–nature connectedness is increasingly overlain and suppressed by modes of industrial land use, which entails teleconnections and external non-renewable inputs. In this paper we introduced a new approach to conceptualize biophysical human–nature connectedness at regional scales and related it to potential sustainability outcomes. Building on *a priori* state of biophysical connectedness, we identified two major realms of disconnectedness: (1) external non-renewable inputs that enter the land use system and (2) teleconnections with distant systems, both of which decrease regional connectedness.

While the conceptual framework itself represents a novel perspective on land use management, the combined methods for each part are well established. Together these methods allow for comparisons of different 'types' and degrees of the connectedness between different regions, which in turn can be related to other regional characteristics or sustainability outcomes (e.g. Wittman *et al* 2016). The framework is designed to be applicable to regions anywhere in the world and to encourage researchers and policymakers to develop a more holistic approach regarding cross-scale, sustainable land management issues not captured by other frameworks (e.g. sustainable intensification (Barnes and Thomson 2014, Loos *et al* 2014a), or land sparing (Fischer *et al* 2014)).

Instead of making human–nature connections evermore complex and opaque by increasing external inputs via industrial technology, a genuinely reconnected system will have a higher internal self-reliance, through a more self-sufficient land use system. Such regionally reconnected systems may facilitate more foresightful, responsible and conscious behaviors. We believe that there are various opportunities to strengthen connectedness of humans to nature. For example, by a re-regionalized economy, a higher degree of self-sufficiency, lower degrees of dependence on external (non-renewable or distant) inputs, by internal biomass reuse (Galán *et al* 2016, Tello *et al* 2016), permaculture, agroforestry, organic farming, small-scale farming, low external input technology farming (Tripp 2005), lower consumption patterns (especially of NPP intensive products, like animal products), less overproduction and consequently less food and biomass 'wastes'. The operationalization of this model can be applied as a heuristic tool to reveal complex social–ecological interlinkages, raising awareness of the challenge in managing biophysical connections across scales. This in turn might help to shift the focus from 'on site' efficiency thinking in land use management to a more comprehensible and holistic perspective on human–nature connectedness.

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