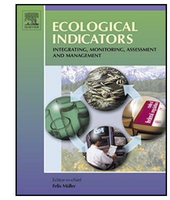
Ecological Indicators 41 (2014) 1–14

Contents lists available at ScienceDirect

Ecological Indicators

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



The impact of nuclear accidents on provisioning ecosystem services

Fabienne Gralla[a,d,*], David J. Abson[b], Anders P. Møller[c], Daniel J. Lang[d], Henrik von Wehrden[a,e]

[a] Centre of Methods, Leuphana University Lueneburg, Scharnhorststr. 1, 21335 Lueneburg, Germany
[b] FuturES Research Center, Leuphana University Lueneburg, Scharnhorststr. 1, 21335 Lueneburg, Germany
[c] Laboratoire d'Ecologie, Systématique et Evolution, CNRS UMR 8079, Université Paris-Sud, Bâtiment 362, F-91405 Orsay Cedex, France
[d] Institute of Transdisciplinarity and Ethics, Leuphana University Lueneburg, Scharnhorststr. 1, 21335 Lueneburg, Germany
[e] Institute of Ecology, Leuphana University Lueneburg, Scharnhorststr. 1, 21335 Lueneburg, Germany

ARTICLE INFO

Article history:
Received 8 July 2013
Received in revised form
26 November 2013
Accepted 20 January 2014

Keywords:
Caesium 137
Chernobyl
Ecosystem services
Fukushima
Nuclear accident

ABSTRACT

Nuclear accidents lead to widespread radioactive contamination of ecosystems and related ecosystem services, with potentially serious consequences for human well-being. Based on an initial exploratory analysis of peer-reviewed articles related to Chernobyl and Fukushima, we identified papers which measured increased Cs-137 levels in provisioning ecosystem services. We used a standardized review-protocol to assess (1) whether peer-reviewed science provides sufficient data density and spatial coverage to provide a coherent and comprehensive map of the global impacts of nuclear accidents on provisioning of ecosystem services; (2) whether such impacts are reported in a standardized and reproducible way; and (3) how different safety thresholds affect the availability of food and fodder for human consumption. Based on an initial analysis of approximately 3000 articles, we identified 121 publications that measured Caesium-137 levels in food, fodder and wood. We found that the comprehensive mapping of the impacts of nuclear accidents on provisioning ecosystem services requires a considerable increase in peer-reviewed assessments, including assessment of existing grey literature. Assessments should follow a coherent protocol, providing consistent information on sampling location and the identification of provisioning ecosystem services. There should be a critical dialogue on maximum allowable radiation levels in provisioning ecosystem services and the impacts of such safe appropriation thresholds on human well-being.

1. Introduction

Nuclear power plants are primary energy sources for 30 nations (IAEA, 2013). It has been suggested that 45 countries are actively considering embarking upon nuclear energy programmes (World Nuclear Association, 2014). Nuclear power is often described as a more sustainable energy solution than fossil fuels (Sokolov and Beatty, 2009) due to the lower direct emissions of greenhouse gases (IAEA, 2012). However, the potential environmental damage from nuclear power generation is not limited to their normal operations, but also the long-term direct and indirect effects of nuclear accidents (Dangerman and Schellnhuber, 2013; Macfarlane, 2011). Although nuclear accidents are low-frequency events, they can cause long term impacts on a broad spatial scale that have to be considered in the cost–benefits analysis for nuclear energy use. Therefore, assessments of the "sustainability" of nuclear energy must also consider the full impacts of its generation, critically, including the environmental and socio-economic impacts of nuclear accidents on the environment.

There have been two major nuclear accidents: Chernobyl (Ukraine, 1986) and Fukushima (Japan, 2011) which released Caesium 137 isotopes into the atmosphere (Lelieveld et al., 2012). In response to these accidents monitoring programmes have been put in place to measure ambient atmospheric gamma radiation, for example, the European Radiological Data Exchange Platform (EURDEP) with approximately 3900 monitoring stations in 33 European countries generates hourly measurements (Vries et al., 2005). While such monitoring indicates where potential problems might occur, they do not provide meaningful data regarding the environmental and socio-economic impacts of nuclear accidents. There has been considerable research carried out to evaluate the direct impact of nuclear accidents on human health (e.g. Hoeve and Jacobson, 2012; Baverstock and Williams, 2006; Ilyin et al., 1990),

* Corresponding author at: Centre of Methods, Leuphana University Lueneburg, Scharnhorststr. 1, 21335 Lueneburg, Germany. Tel.: +49 4131 677 1438.
E-mail address: fabienne.gralla@leuphana.de (F. Gralla).

1470-160X/$ – see front matter © 2014 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ecolind.2014.01.027

but less focus on the indirect impacts on human well-being mediated through changes to ecosystems.

Long-term ecological studies are important for understanding and quantifying the effects of radiation in ecosystems across generations (Garnier-Laplace et al., 2011). Several studies have investigated how radioactive substances affect migration and uptake in food chains and ecosystems (e.g. Beresford et al., 2012; Møller and Mousseau, 2007), but ecological impact assessment studies are limited (Møller and Mousseau, 2006, 2013) and a clear and integrated research agenda on the impacts of nuclear accident on ecosystems from ecological processes through to human appropriation of ecosystem functions has yet to be developed (Wehrden et al., 2012). In particular the long-term impacts on ecosystem services are unknown.

Increased radioactivity within ecosystems following nuclear accidents potentially reduces the availability of those ecosystems to provide ecosystem goods and services that contribute to human well-being. National and international regulations have been implemented to set the maximum permissible levels of radioactivity in food and fodder. Adherence to such legally binding regulations—intended to minimize harm to human health—reduces the ability of humans to use these ecosystem services to increase their well-being.

The Millennium Ecosystem Assessment categorizes services provided by ecosystems into four different types: supporting, regulating, cultural and provisioning services (MEA, 2005). Following nuclear accidents, supporting ecosystem services such as nutrient cycling may be affected by the occurrence of long-lived and persistent nuclides such as Cs-137 through the disruption of ecosystem functions. Regulating ecosystem services such as flood protection from wetlands (Froehlich and Wallich, 1994) may be affected, for instance, by remediation measures to limit radioactive contamination (Davydchuk, 1997). Cultural ecosystem services impacted by nuclear accidents are often associated with cultural practices related to provisioning ecosystem services such as mushroom gathering (Druzhinina and Palma-Oliveira, 2004). Provisioning ecosystem services—the goods obtained by the ecosystems, for instance food, fresh-water, wood, fibre and fuel (MEA, 2005)—are the most directly affected ecosystem services types from nuclear accidents. It has been suggested that provisioning ecosystem services strongly determine human-well-being (Raudsepp-Hearne et al., 2010). It is therefore vital that we can quantify the effects of such thresholds on the availability of provisioning ecosystem services after nuclear accidents.

The composition and interrelations of factors influencing Cs-137 accumulation in ecosystems are site specific, and complex—due to issues such as bioaccumulation (Oleksyka et al., 2002), making broad scale generalization of evolving impacts on flora and fauna difficult (Beresford et al., 2007). As a consequence of these difficulties considerable data is required to accurately assess the impacts of nuclear accidents on ecosystems and their related services.

Here, we focus on assessing the known impact of nuclear accidents on provisioning ecosystem services as identified in the peer-reviewed literature. We acknowledge that there is a large body of grey literature in the form of national monitoring reports on radioactivity levels in provisioning ecosystem services (e.g. MHLW, 2013a; EC, 2009). There are also monographs focusing on the impacts of Chernobyl and Fukushima on food and agriculture (Nakanishi and Tanoi, 2013; Moberg, 1991). However, here we focus on peer-reviewed publications since this literature is not limited by national boundaries; provides reproduceable results; additional contextual information regaring the dynamics, interactions and impact of nuclear accidents; and draw conclusions regarding research gaps and shortcommings. There are peer-reviewed studies that report radiation levels in a single provisioning ecosystem service across large spatial scales (e.g. Lavi et al., 2006; Kalac, 2001; Mietelski et al., 1994), but these studies only provide a partial view of the impact of nuclear accidents on provisioning ecosystem services. We assess the extent to which the peer-reviewed science can be used to quantify the impacts of Cs-137 contamination on provisioning ecosystem services, with a specific focus on food, fodder and wood, after major nuclear accidents.

We addressed three aims: (1) whether the peer-reviewed science provides sufficient data density and coverage to provide a coherent and comprehensive map of the global impacts of nuclear accidents on provision ecosystem services (which we refer to as a coherent impact grid); (2) whether scientific publications are reporting monitoring results in a standardized and reproducible way; and (3) how different permissible radiation thresholds affect the availability of food and fodder and therefore human well-being.

2. Material and methods

We conducted a quantitative and qualitative review of peer-reviewed studies focusing on the sampling of radioactivity in food, fodder and wood after nuclear accidents. First we identified all publications ("full papers" in English and German) via the Scopus database (April 2012) with two search strings (see Appendix A) including "Chernobyl" (all papers since 1986) and "Fukushima" (all papers since 2011). This search returned approximately 3300 papers. A second search on "Fukushima" to include recent papers was conducted in November 2012 returning 76 studies.

2.1. Selection process of peer-reviewed papers

We limited the analysis to studies that measured caesium-137 radioactivity (subsequently Cs-137) as the highest radiation dose to the human population after the Chernobyl and Fukushima nuclear accidents was caused by Cs-137 deposition (Tracy et al., 2013). Moreover, Cs-137 has a half-life of 30 years, allowing long-term impacts of radioactive accumulation on provisioning ecosystem services to be analyzed. We considered only Becquerels (Bq) measurements, because this measure is used to set maximum permissible levels (thresholds) of radioactivity of goods that can be sold. One Bq describes the activity of radionuclides in which one nucleus decays per second on average (Kalac, 2001). We acknowledge that provisioning ecosystem services can be negatively affected by genetic changes as a result of radioactive accumulation in plants (Kuchma et al., 2011; Kovalchuk et al., 2003) and animals (Røed and Jacobsen, 1995). Nevertheless, these impacts were not included in our analyses because more knowledge is needed to understand the evolving consequences of mutations (Kuchma et al., 2011) on provisioning ecosystem services.

We had institutional access to 1873 of the 2050 studies dealing explicitly with monitoring results and measurements on ecosystem services. We only included papers in the analysis (Chernobyl ($n = 118$) and Fukushima ($n = 3$)) that reported actual Cs-137 radioactivity levels—illustrated or mentioned in the text, tables or graphically—exceeding those set by the Japanese authorities after Fukushima for food (MHLW, 2013b) and fodder (IRSN, 2012), as we deemed this to be the lower bound threshold below which the provision of the associated service would not be effected (Table 1). Since no thresholds have been set for wood, we applied the recommendation of 750 Bq/kg for stemwood from the National Ukrainian wood utilization (Davydchuk, 1999) and 100 Bq/kg for other wood samples (bark, twigs, shoots), as assumed by Hubbard et al. (2002) for fuel-wood. Here we should note that we did not limit the analysis to those studies that explicitly referred to the consumption of the flora and fauna under study. Therefore, this analysis relates to