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STRENGTHS OF ECOSYSTEM SERVICES CONCEPT FOR RADIATION PROTECTION

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The successful ecosystem services concept, defined as the benefits people obtain from ecosystems is still not really reflected in the current approaches for protecting public and environment against radiation promoted by the International Commission on Radiological Protection or other similar approaches. Yet some recent thoughts from international organizations lead us to believe that an eco-based approach could be more promoted in the coming years in environmental radiation protection field. The French Institute for Radiation Protection and Nuclear Safety has identified different fields of application of this concept into radiation protection, in line with its integrated approach of radiological risks management. As the ecosystem services approach makes it possible to highlight biophysical and socio-economic approaches of the impacts of ionizing radiation on ecosystems, it represents a subject of primary importance for future works conducted by IRSN.

However, the operationality of the ecosystem services concept is the subject of many debates. In many situations, scientists have not yet fully understood how radioactive contamination could affect ecosystem services, and how to articulate with certainty cause and effect relationships between state of an ecosystem and provision of services. In addition, the concept is also accompanied by contradictory perceptions of the status of humans in ecosystems. To solve these knowledge gaps and uncertainties, it is necessary to acquire robust data on the impacts of radiation on ecosystems both under experimental and realistic conditions, and to integrate all potential consequences (direct and indirect, ecotoxicological but also economic and cultural).

The concept of ecosystem service was highlighted through the United Nation's Millennium Ecosystem Assessment in 2005 1 (see 1 for a history of this concept). It refers to goods and services that people can derive from ecosystems, directly or indirectly, to ensure their well-being. Four categories of ecosystem services are generally distinguished:

- provisioning services (products obtained from ecosystems), e.g.: food (agriculture, fishing, aquaculture, wild plants, animal feed), wood and fuels, water, fibers (such as cotton), human and veterinary health drugs, which are directly used by people.
- regulating services (benefits obtained from regulation of ecosystem processes), e.g.: climate regulation, regulation of water flows, erosion regulation, pollination, biological control.
- cultural services (non-material benefits that arise from human-ecosystem relationships), e.g.: aesthetic experiences, spiritual enrichment, recreation, cognition development.
- supporting services (services that are necessary to produce all other ecosystem services) e.g., soil formation or primary production. In some classifications, supporting services are considered as ecosystem functions rather than services. These functions ensure the proper functioning of the biosphere such as major biogeochemical cycles (water, carbon, etc.). These functions correspond to the intrinsic characteristics of ecosystems (decomposition, production, nutrient cycle, flow of matter and energy, etc.) by which they maintain their integrity.

Among current approaches aimed at better considering interactions between people and nature, the ecosystem services approach has been developed over the past two decades and is gradually tending to become a reference framework for the assessment and the management of ecosystems. It draws attention to the benefits that ecosystems generate for society and raises awareness for biodiversity conservation. It makes it possible to communicate and alert on the human dependence from ecosystems and conveys a vision of ecosystems that emphasizes the multiple interactions between its components. Its promotion facilitates the collaboration and the dialogue between different disciplines on most environmental issues (such as climate change or biodiversity loss). Through this integrative approach, it makes it possible to translate complex ecological processes into a common, simple and accessible vocabulary. Indeed, the complexity of the functioning of ecosystem could be better understood by underlying the importance of ecosystem services provided by nature to the human well-being (including how the disturbance of the functioning of ecosystem will lead to consequences for the whole human world) 2.

Although this concept is intuitively appealing and easily understandable, its operationalization remains a challenge. Currently, the ecosystem services framework is mainly developed in the field of environmental policies, such as those of the European Union and its "Biodiversity Strategy for 2020" 4 in which the protection of biodiversity is intimately linked to the protection and the restoration of ecosystem services. The concept is thus increasingly used to define environmental protection objectives (forest protection, marine protection, biodiversity conservation…) and to assess the impacts of the main drivers of environmental change such as climate change, land use change, pollution.

In the radiation protection field, the concept of ecosystem service is currently little used but seems to be a promising concept for providing a coherent framework encompassing both the radiation protection of human and non-human species, facing a radiological contamination. Until now, as other equivalent national and international organizations specialized in radiological risks, the French Institute on radiation protection and nuclear safety (IRSN) has considered these two fields relatively separately. Although scientific works assessing the effects of ionizing radiation on the production of ecosystem services remains very limited, there is a growing interest in characterizing the impacts of radionuclides on ecosystem services in a holistic way. This includes the assessment of direct effects of radionuclides on the environment, i.e., toxicity on non-human species and on ecosystem functions, but also the indirect consequences, i.e., the loss or the degradation of ecosystem services as a result of a radiological contamination.

APPLICATION OF THE ECOSYSTEM SERVICE FRAMEWORK IN THE INTERNATIONAL SYSTEM OF RADIATION PROTECTION

The identification of the need for protecting environment (non-human biota) against radiation is quite recent. Until 1991, ecosystems were only considered as vectors of human exposure, and people were the priority object to be protected. Assuming that human is the most radiosensitive species, protecting it would amount to not endangering non-human species [5].

In 1992, the International Atomic Energy Agency (IAEA) proposed to adopt reference values specific to non-human biota. These values are expressed in exposure dose rates (under which deleterious effects on taxonomic groups would not be observed).

From the 2000's, the awareness of the importance of protecting the environment from the risks associated to ionizing radiation gradually increased.

In 2005, the International Commission on Radiation Protection (ICRP) created a committee dedicated to the radiation protection of the environment (Committee 5) taking into account the fact that [6]:

- consideration of the environment must be more explicit, particularly as regards the growing concerns of society for biodiversity and ecosystems conservation,
- regulatory requirements, such as European Community directives, increasingly integrate the notions of environmental protection in a broad sense,
- the demonstration of the effective protection of the environment was not ensured in the previous system,
- the previous system was not consistent with assessment methods of other stressors (such as chemical contaminants).

Since then, the objective of protection became to "prevent or reduce *the frequency of deleterious radiation effects to a level where they would have a negligible impact on the maintenance of biological diversity, the conservation of species, protection, or the health and status of natural habitats, communities and ecosystems*" [7]. This evolution is at the origin of the financing by the European Community of a series of scientific programs which resulted in the development of methodologies, tools, and databases dedicated to the assessment and management of environmental risks from ionising radiation such as the ERICA tool (Environmental Risk from Ionising Contaminants Assessment and Management) [8] and the FREDERICA radiation effects database.

In 2008, ICRP provides a methodology to protect non-human biota similar to the one used in human radiological protection (i.e., Reference Man): the "reference animals and plants" (RAP) approach. This approach was notably developed by Committee 5 to assess environmental risks and is the subject of ICRP publication 108 [7]. Since that date, ICRP considers the protection of the environment in a similar way to the protection of public, by establishing the characteristics of the object of protection through the constitution of databases for twelve reference animals and plants (RAP), exposure scenarios, dose-effect relationships. However, for some radiation protection experts, the representation of nature in the form of a list of RAPs remains simplistic and could be more realistic. Since RAPs are restricted to a few animals and plants taxa defined at family level and sometimes purely theoretical for entire animal or plant groups (e.g., "eusocial bee" defining all types of insects [7]), they do not include either basic difference in species lifestyles, physiology, or morphology. Moreover, even though the experience feedback from the consequences of the Chernobyl and Fukushima nuclear accidents shows that while some RAPs did not receive any dose likely to affect them (which means, according to the ICRP's approach, that environment was protected), some ecosystem services were affected. Indeed, the radiological contamination of ecosystems (agricultural, aquatic and forest mainly) has contributed to the loss or the degradation of some ecosystem services (provisioning services e.g., food, fish, wood and cultural service e.g., hunting, gathering and other recreative services) which are not integrated in the RAP approach.

In 2014, following the recommendations of the ICRP, the IAEA revised its international standards for radiation protection by explicitly mentioning environmental protection in a chapter dedicated to the effects of exposure to ionizing radiation [9]. It incorporates the latest recommendations from the ICRP [10] and aims to achieve two radiation protection goals: " *protect ecosystem services in order to guarantee for present and future human generations a sustainable use of environmental resources useful to agriculture, forestry, fishing, tourism; prevent the effects of ionizing radiation on non-human biota*".

In 2021, in its draft revision of the radiation protection standards [11], ICRP pointed out that it plans to take greater account of more holistic considerations integrating ecosystem services in environmental protection and thus to gradually move from an anthropocentric approach to a more ecosystem-oriented one. This last approach incorporates parameters related not only to individual organisms but also to communities (plant, animal, and microorganisms) and ecosystem functions. To develop this holistic approach, additional knowledge on the effects of radiation on ecosystem structure and function will be needed.

ASSESSING THE IMPACT OF IONIZING RADIATION ON ECOSYSTEM FUNCTIONS AND SERVICES: A NEW PERSPECTIVE FOR RESEARCH AND EXPERTISE AT IRSN

As the Millenium Ecosystem Assessment pointed out in 2005 [1], the assessment of the impacts of anthropogenic stressors (such as radioactive pollution) on the structure and functions of ecosystems is essential to optimize the management of ecosystem goods and services. Indeed, nuclear activities are potential drivers of change in ecosystems, affecting their state, structure and functioning. Increased radioactivity in ecosystems following nuclear accidents can negatively impact the biodiversity and the functioning of ecosystems, and thus reduce the capacity of ecosystems to provide ecosystem services that contribute to human well-being ([12],[13]).

To understand and predict the risks that radionuclides represent for the production of ecosystem services, it is necessary to be able to measure their impacts on ecosystem functions that support the production of ecosystem services. If the cultural, social and psychological repercussions of nuclear accidents are partially documented since the Fukushima accident (e.g., [14]), there are only very few studies on how ionizing radiation affects ecosystem functions ([15], [**Erreur ! Source du renvoi introuvable.**]) probably because this characterization remains a complex and difficult area to grasp. Moreover, the few studies that has attempted to deal with the issue has not revealed yet any notable impacts on specific ecosystem functions excepted for a few highly contaminated areas such as the soils of the Techa river basin in Urals [17] or the dead pine forest of Chernobyl ([15],[18]). At Chernobyl, changes in the structure of grassy communities within the area of dead pine stands led to a 2–3 fold increase of grass-cover biomass [18] and a decrease in the rate of leaf litter decomposition and an increase in the thickness of the litter on the ground related to an increase in ambient radioactivity [15]. These results suggest slower recycling of organic matter in response to a higher level of ambient radioactivity, possibly due to a negative impact on communities of decomposers (bacteria, fungi, detritivores invertebrates).

The effects of radiation on some specific ecosystem functions are currently studied by IRSN. Among the ongoing projects, the IRRASOIL project aims to quantify the effects of ionizing radiation on soil communities and associated functional processes in interaction with predicted climate change. More specifically, using a combined approach of laboratory experiments under controlled conditions (mesocosms) and field assessments (Chernobyl and Fukushima regions), this project aims: (i) to quantify the effects of ionizing radiation in interaction with increased temperatures and decreased water availability on soil community structure and processes related to the transfer and transformation of organic matter (bioturbation, leaf litter decomposition…); (ii) to quantify how different functional groups of the soil macrofauna community, such as earthworms (endofauna) and litter layer-dwelling macrofauna (epifauna) interactively affect decomposition processes under contrasting conditions of ionizing radiation and soil moisture and temperature. In this project, the use of the ecosystem service concept would make it possible to better communicate on the results and make them more accessible to a wide audience. It would also better underline the fundamental role of soils in the production of many ecosystem services and functions (e.g., food, biomass production, water purification) and therefore the importance of studying the effects of radiological contamination on soils (quality, fertility…). This work, aimed at characterizing the effects of ionizing radiation on the functional processes of ecosystems, will make it possible to test the use of decomposition rates as a functional indicator of the state of the health of contaminated ecosystems and thereby to have an operational tool to assess remediation actions for impacted ecosystems. However, this type of approach remains complex because there are still significant methodological difficulties linked to the complexity and diversity of soil ecosystems.

If the characterization of the effects on ecological functions and ecosystems, can be complex, the identification of the ecosystem services impacted seems easier. Indeed, a nuclear accident is likely to partially or totally degrade many ecosystem services [19] : provisioning services (e.g., food, fibers, wood harvesting, aquaculture, professional fishing), supporting services (e.g., support for food crops or energy crops; water supply for domestic, agricultural or industrial use), regulating services (maintenance of soil quality, contribution of pollination to the production of food resources, maintenance of biodiversity), cultural services (landscape in the aesthetic sense, biodiversity and heritage (protected sites, protected and emblematic species), hunting, recreational fishing, nature sports, etc.). The benefits associated with these services may be interrupted if the radioactive contamination disrupts the ecological functions of the ecosystems or when competent authorities decide to put in place restrictions on human activities which depend on them.

Although a wide range of ecosystem services could be negatively affected by a radiological contamination, most studies on the effects of radiation on non-human biota do not directly mention ecosystem services but rather the maintenance of biodiversity (e.g., quantification of the abundance of mammals in the Chernobyl zone [20]). The few articles or monographs (Fukushima, Chernobyl) that address the concept of ecosystem services do so solely from the perspective of provisioning services since they are most directly affected by the few nuclear accidents that have already occurred, due to administrative restrictions on use or consumption of goods related to contamination levels (food, fresh water, wood, fiber).

As regards agricultural ecosystems, several studies show that the Fukushima accident caused the contamination of large areas that were used for agricultural purposes which led for exceedances of the limits in activity concentrations in food (vegetables, fruits, mushrooms, tea leaves…) [21]. This contamination affected the corresponding provisioning services. Moreover, lessons learned by IRSN from remediation strategies in Fukushima show that some protective countermeasures may have undesirable effects on ecosystems and ecosystem services [22]. In some cases, if the ambient dose rate has been greatly reduced, the choice of a remediation technique (soil leveling, turning over of the topsoil layer, deep ploughing) can have a long-term impact on soil fertility (for example, despite the drastic decontamination measures employed, the sales of anpokakis (Japanese fruit) was only able to restart in 2015, the contamination having previously exceeded current standards). The choice of a remediation technology or strategy should include criteria related to ecosystem services maintained or restored, by integrating, in the decision-making process, parameters such as protection of the ecosystem and preservation of ecosystem services. This would avoid counterproductive actions generating more disadvantages than benefits, by integrating economic, social and environmental factors, in a holistic approach. ICRP 146 on nuclear accidents [23] also emphasizes the importance of taking into account the damage to ecosystem and ecosystem services induced by protective countermeasures.

Including the ecosystem services approach in the reflection on post-accident recovery management would thus make it possible to enrich criteria considered in the choice of options and countermeasures to consider (prioritization of the territories to be decontaminated, choice of decontamination technique, etc.) in order to minimize impacts on ecosystem services, or to contribute to the restoration of degraded or lost services. The effectiveness of the actions linked to the post-accident recovery management could better integrate the expected effects on ecosystem services in addition to the health criteria (doses avoided for the population/doses received by the workers) already adopted (which are sometimes already combined with economic criteria (maintaining economic activity/image of territories and products) or societal (rehabilitation of confidence/return of the population).

As regards forest ecosystems, the studies carried out by IRSN have made it possible to consider provisioning services for non-wood forest products and recreational services (associated with the practice of hunting and gathering). The value (or cost) of the loss of these services has been estimated using a tool (ARPAGON) developed by IRSN: this software dedicated to economic expertise makes it possible to estimate the direct costs associated with post-accident actions. As part of a multi-partner project on a hypothetical nuclear accident in France (AMORAD project), the economic costs linked to the loss of services linked to forest ecosystems (hunting, gathering, wood production) have been assessed. The results of the French case study [24] show the importance of taking non-market costs into account for decision making process related to post-accident recovery management. The main contribution of this work is to have carried out, for the first time, an economic assessment of the loss of forest ecosystem services impacted by a radiological contamination after a major nuclear accident. Other ecosystem services (such as carbon storage, moderation by evapotranspiration of local climate variations, recycling and purification of water, limitation of soil erosion, provision of habitats) could be considered in the future within the framework of a similar study but for this, it will be necessary to have access to eco-toxicological data which are not currently available. This remains a research prospect for the future for IRSN.

Concerning aquatic ecosystems, the sensitivity of ecosystem, considering the ecosystem services provided, has also been assessed by IRSN for French rivers as part of a project dedicated to the modeling of the dispersion of radionuclides in French rivers after a nuclear accident [25]. A prioritization and a selection of watercourses to be modeled was carried out to identify those whose contamination would be most likely to present a health, environmental and social issue, considering a diversity of accident scenarios as well as vulnerability parameters. The issues considered (health, economic and ecological) were aggregated as part of a multi-criteria analysis. The assessment of the territorial vulnerability was based on an eco-centered approach considering the ecosystem services provided by rivers which are the most sensitive to water quality (aquaculture, bathing, fishing) and their importance or value for the beneficiaries. Then, mapping of the issues associated with these services was established based on available economic data or values estimations for non-market services (data on willingness to pay for access to beaches, value of diving areas, value linked to the presence of a marine biocenosis). Environmental sensitivity criterias such as ecological diversity were also taken into account, which made it possible to establish global sensitivity maps, helpful for post-accident recovery management. This holistic approach considers, in the definition of post-accident management strategies, the uses of the water and of watersheds degraded after a radiological contamination. In this context, the use of the ecosystem service concept is useful for assessing direct and indirect consequences on the marine environment. Such maps of territorial sensitivity could also help decision-makers in the choice of areas to be protected as a priority against pollution (chemical, hydrocarbons, radiological) as well as in the identification of use restrictions (on bathing, fishing) to be implemented. The continuation of this work is directed towards the evaluation of non-market activities (recreational in particular) and the benefits resulting from the marine ecosystems of the Mediterranean Sea [26].

For all types of ecosystems (agricultural, forest, marine), a common assessment framework could be developed. Based on the methodology proposed by the French National Institute for Agriculture, Food and Environment (INRAE) in 2021 [27], this method could make it possible to identify priority ecosystem services to be taken into account in post-accident impact assessments and the definition of remediation strategies and associated countermeasures, in order to reduce impacts on of priority ecosystem services. This method could include:

- delimitation of impacted zones (directly and indirectly),
- qualification or quantification of existing ecosystem services in the impacted area,
- determination of ecosystem services to be taken into account for impact assessment, involving current beneficiaries, if possible,
- identification and quantification of those which are impacted by radiological contamination,
- assessment of gain and loss in the production of ecosystem services,
- determination of remediation scenarios with the least impact on ecosystem services.

Until now, there is still a lack of exhaustive analyzes of direct and indirect effects of ionizing radiation on different types of ecosystem services (provisioning, regulating, cultural) in contaminated territories. Such analyzes presuppose a mobilization of multidisciplinary teams (biology, ecotoxicology, environmental economy, human and social sciences, etc.) able to assess the impacts not only in biophysical and ecotoxicological terms, but also in economic and socio-cultural terms. This would also require a capacity to establish dose-response relationships for the production of these services. For example, relationships between contamination or exposure levels and types of effect could be developed for some ecosystem services, mainly provisioning services (food, wood, fishing, etc.) for which there are, in certain cases, reference thresholds for their consumption and selling. For this kind of services, the effect is quantifiable based on the level of contamination. Depending on the level of contamination of wood, it can no longer be sold. Similarly, depending on the level of contamination of a forest, the access to the forest will no longer be authorized for recreational activities or hunting. For other types of ecosystem services, a dedicated methodology and metric would need to be developed because there is no direct relationship between the level of contamination and the consequences for these services. There is rather a loss or a degradation of the service mainly resulting from administrative restrictions decided by authorities. For this type of indirect effects, economic assessment could offer new research perspectives.

CONCLUSION

In recent years, the radiation protection system has evolved from an anthropocentric perspective to one encompassing non-human biota. To support this evolution, it remains necessary to promote a holistic approach integrating ecosystem services in environmental risk assessments, aiming to better take into account interactions between people and their environment. In this context, the emergence of the ecosystem services concept in the field of environmental protection offers a global approach to the functioning of an ecosystem and an ability to explicitly link ecological and biophysical issues with sociocultural and economic issues. This approach helps to emphasizes that changes or impacts on one part of an ecosystem have consequences for the whole system. It also offers a framework for exchanges and interface between scientists, beneficiaries of services and decision makers, combining a plurality of issues. In terms of communication and interaction with the public, the concept constitutes a simpler and more comprehensible notion to evoke complex issues (in comparison to technical terms conventionally used in the field of environmental radiation protection such as doses, dose rates, radiation thresholds, permissible levels in foodstuffs). Finally, the concept offers a frame that allows to integrate non- market or intrinsic values of environment which facilitate debates and support decision-making process.

Although the concept of ecosystem services is now largely institutionalized and its educational dimension well established since the publication of the Millennium Ecosystem Assessment in 2005, the operational dimension of the concept is the subject of many debates, and the concept is also accompanied by some controversies [28]. These controversies are mostly linked to the fact that scientists are not always able to state with certainty cause and effect relationships between the state of an ecosystem and the production of ecosystem services. Moreover, there is still a lack of robust scientific data to understand how radionuclides affect biodiversity and ecosystem services and to mitigate the associated impacts. Specifically, the question of knowing at what dose rates, ionizing radiation represents a long-term danger to ecosystems remains controversial and constitutes a priority for radiation protection research conducted by IRSN.

In addition to these scientific uncertainties, the concept is also accompanied by societal uncertainties which refer to the existence of differentiated, even contradictory perceptions of the concept of service and of the status of humans in ecosystems [**Erreur ! Source du renvoi introuvable.**]. For some authors

([30], [31]), this approach gives priority to the logics of economic and social self-interest over any ethical imperatives for the intrinsic value of different entities in nature. In fact, it all depends on the acceptance of ecosystem services boundaries: indeed, if ecosystem services provide benefits to people, some of them also provide benefits to nature itself.

Beyond these controversies, the concept of ecosystem services remains a topic of primary importance in the field of radiological and nuclear risk assessment and deserves to be more widely integrated in studies on the consequences of radiological contaminations and nuclear accidents. For this, it will be necessary to acquire robust data on the effects of radiation on ecosystems both under experimental and realistic conditions, and by integrating all consequences, direct and indirect, ecotoxicological, economic and socio-cultural.

In the coming years, it is likely that the radiation protection system, based on practical implications (such as protection of reference animals and plants) considered as perfectible, will evolve towards a vision based on better understanding of the functioning of ecosystems and the protection of the services they provide to humankind. Rather than seeking to develop more sophisticated models around reference organisms, concepts such as ecological functions and ecosystem services could be new subjects of research work.

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