Touching the Grass: Science, Uncertainty and Everyday Life from Chernobyl to Fukushima

TESSA MORRIS-SUZUKI

The Fukushima nuclear disaster of March 2011 raises profound questions, not only about the use of nuclear energy, but also about the way in which scientific knowledge is constructed and communicated. This article focuses particularly on the divergent ways in which the notion of 'uncertainty' is understood by scientists and scientific bodies engaged in studying the effects of the Chernobyl and Fukushima disasters, and by the residents who are the main victims of these disasters. I argue that the approach to uncertainty and risk assessment developed by bodies like UNSCEAR and the Chernobyl Forum has been applied in Fukushima in ways that have widened the gap in understanding between academic scientists and local residents, but I also point to experiments in citizen science that have potential to help bridge this gap.

The Sign in the Park

I AM HAUNTED by the image of a fleeting moment—not a moment that I witnessed myself, but one recounted to me by the friend who saw it. A small child, born in Fukushima Prefecture around the time of the March 2011 nuclear disaster, is on holiday in a part of Japan far from his home. He runs through a park, arms stretched wide, face beaming, eyes shining with excitement at the glorious world around him. At the age of two-going-on-three, he has never played out of doors before. He has just touched grass for the first time.

To many experts, this scene would seem absurd. Levels of radiation in the area of Fukushima where the child lives—though higher than normal—are, on average, well below the levels that the Japanese state, the International Atomic Energy Agency (IAEA) and other institutions define as posing a serious risk to health. This seems like a good illustration of the conclusions reached by the 2005 official UN-sponsored Chernobyl Forum report on the 1986 nuclear disaster in the Soviet Union: that mental problems such as psychological fear of radiation cause

Tessa Morris-Suzuki, College of Asia and the Pacific, Australian National University.
E-mail: tmorrissuzuki@gmail.com

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more harm than radiation itself (Chernobyl Forum, 2006, p. 36). In the words of the Chernobyl Forum (made up of experts from eight United Nations bodies including the IAEA and the World Health Organization), these problems take the form of ‘strongly negative perceptions of health and well-being’; ‘an exaggerated sense of the dangers to health of exposure to radiation’; and ‘a widespread belief that exposed people are in some way condemned to a shorter life expectancy’. ‘Parents’, the report admonishes, ‘may be transferring their anxiety to children through example and excessively protective care’ (Chernobyl Forum, 2006, p. 36). From this perspective, the small child’s parents are not only damaging his physical health—since lack of outdoor exercise poses a far greater risk than any likely threat from radiation—but also passing on ‘exaggerated or misplaced health fears’ and a dangerous ‘sense of victimisation and dependency’ (Chernobyl Forum, 2006, p. 37).

From another point of view—the viewpoint of many Fukushima residents—it is not the actions of the parents that are absurd. Rather, since the March 2011 series of explosions and meltdowns in TEPCOs Fukushima Dai-ichi nuclear power plant, life as a whole has come to be imbued with the absurd in a different sense of the word: the sense that the world ‘which one might have thought to be amenable to reason...turns out to be beyond the limits of rationality’ (Cornwell, 2006, p. 2). In this Kafkaesque world, the foundations of everyday life, even the laws of nature themselves, have slipped in some ill-defined way. Isolated individuals face a series of ‘alarmingly incomprehensible predicaments’ (Baldick, 2008, p. 1; Cornwell, 2006, p. 2; see also Beck, 2009, p. 6). Their responses to those predicaments are then held up to public scrutiny and judgement, even though there can be no certainty yet whether the responses were right or wrong. The realities of living in this absurd world have been vividly described by many who experienced the aftermath of the disaster in Fukushima (for example, Arakida, 2013; Ichisawa and Ichisawa, 2013; Kondō and Ōhashi, 2013; Shoji, 2013).

In the park opposite my Fukushima City hotel, poking up amongst the luxuriant summer grass and weeds, stand two signs. One gives the most recent radiation reading: 0.34 microsieverts per hour. This is more than ten times the radiation reading given on the sign posted in my hotel lobby just a couple of hundred meters away, but only about one-eighth of the official reading from Sakabuta Park in the nearby city of Koriyama. Everyone moving through daily tasks in this landscape is being exposed to greatly different levels of radiation each time they cross a street, go in or out of a doorway, or step on or off a bus. Measuring individuals’ level of exposure is a dizzyingly complicated task.

The second sign in the park provides these courteously worded instructions to users:

> *Because of the effects of environmental radiation, please pay attention to the following points:*
>
> *please limit your use of this park to one hour per day;*
> *after spending time in this park, please wash your hands and face, and gargle;*
> *please take care not to put earth or sand in your mouth.*

The last instruction might seem superfluous, unless addressed to very small children. Most likely, though, it is addressed to parents (usually mothers) who may bring small children to play in the park; in which case the instruction seems eminently sensible; unless (for example) you happen to be a mother trying in vain to pursue a fast-moving three-year-old through the undergrowth while at the same time pacifying a five-year-old who has just decided to sit on the ground and have a tantrum. In which case it is also quite likely that when you go home, and the five-year-old resolutely refuses to wash her hands, you will abandon the effort to persuade her for fear of provoking further tantrums, while you attend to the challenging task of rinsing out the mouth of the squirming three-year-old whom you suspect of having tried to eat sand. It is of such mundane disasters that everyday life is made.

In this instance, the mother might be seen as exhibiting the other main mental problem identified by the members of the Chernobyl Forum, who note that the 'paralysing fatalism' of local people exhibits itself, paradoxically, not only in 'excessively cautious behaviour (constant anxiety about health)', but also simultaneously in wilful disregard for their own (or their family's) health, leading to 'reckless conduct' such as 'consumption of mushrooms, berries and game from areas of high contamination' (Chernobyl Forum, 2006, p. 41).

What happens when the existential disaster of nuclear accident collides with the mundane disasters of everyday life? I shall argue that the collision fractures our concept of rationality. When the uncertainties and complexities of the science of radiation meet the very different uncertainties and complexities of everyday life, scientific rationality and mundane logic diverge, creating profound problems of communication and understanding. Both the Chernobyl Forum report of 2005 and many of the current international reactions to the Fukushima explosion and meltdown of 2011 vividly illustrate this point. The more time passes, the clearer it becomes that the Fukushima disaster not only poses challenges to the use of nuclear power but, at a fundamental level, raises questions about the construction and communication of scientific knowledge.

This article has a particular focus, and does not attempt to address many dimensions of the disaster which, although extremely significant, lie beyond the scope of that focus. My aim is to probe the mismatch between some very influential scientific interpretations of uncertainty and the human experience of indeterminacy as it is lived by people exposed to events like the Fukushima disaster, and to argue for a new and broader approach to the understanding of indeterminacy in everyday life.

Over the past twenty years, 'uncertainty' has become an increasingly crucial concept in science, and scientists have developed a range of sophisticated techniques to analyse and domesticate uncertain phenomena. These techniques have helped shed light on some of the most significant challenges of our times (including climate change and the effects of radiation on health). The problem lies, not in these techniques themselves, but in the way that findings generated by the techniques are applied to the task of understanding the world in which we live. The misapplication of knowledge and the colonisation of everyday life by inappropriate approaches to the understanding of uncertainty are, I believe, a central cause of the profound disorientation and alienation experienced by the victims of the Fukushima disaster. Meanwhile, though, the responses of local residents to the disaster contain the seeds of possible alternative approaches, which may help us to reconsider the relationship between science and everyday life.

Embracing Uncertainty

From 1938 to 1939, the eminent geneticist and passionate Marxist, J.B.S. Haldane published a series of newspaper articles, later compiled into a book entitled *Science and Everyday Life*. These articles inspire popular enthusiasm for science by showing how profoundly the ingredients of our daily existence, beginning from the daily bread on the average British breakfast table, are shaped by scientific innovation. Haldane's message is profoundly optimistic. Science may be misused by capitalist society (he argues) but in the right hands, it can only yield benefits to humanity. Scientists are fallible, but the further knowledge progresses, the closer they come to understanding the truths of the universe. The future is filled with visions of hope:

> …there are physicists who believe that within this century artificial radio-activity will be used as a source of power. If so it will revolutionise human society as completely as did the steam engine, for it will be possible to set up anywhere an engine which will work for centuries without fresh fuel. (Haldane, 1940)

More than seventy years on, the equations of science and everyday life seem a great deal more complicated. A scientific account of the British breakfast table today would need to explore the wide array of colourings, sweeteners, preservatives and other chemical residues that come together in the everyday diet. It would confront us with debates about genetically modified crops, and it might also touch on questions of radiation. Many of the foodstuffs discussed by Haldane contain small amounts of naturally occurring radiation, and in the years since he wrote *Science and Everyday Life*, the global environment has been subtly altered by the dispersal of radioactive substances (such as tritium, iodine 131, caesium 137, plutonium and strontium) that do not occur in nature, but are by-products of atomic weapons testing and industrial uses of atomic energy. These substances are so widely dispersed and at such low levels that their affects on global health are unknown, although there have been cases of damage to health in some areas of high fallout (Advisory Committee on Human Radiation Experiments, 1996). The broader global health effects lies in the realm of uncertainty, and continues to be debated by scientists.

The more complex our technology becomes, and the deeper science penetrates into the inner workings of nature, the more the realm of uncertainty expands. A couple of months before the 2011 Fukushima nuclear accident, the web magazine *Edge* invited prominent scientists and science commentators to respond to the question 'what scientific concept would improve everybody's cognitive toolkit?'

Many of the answers to this question were variants on the same theme: that the most valuable improvement would be learning to embrace uncertainty. As physicist Lawrence Krauss put it, 'in the public parlance, uncertainty is a bad thing, implying a lack of rigour and predictability...In fact, however, uncertainty is a central component of what makes science successful. Being able to quantify uncertainty, and incorporate it into models, is what makes science quantitative, rather than qualitative.' Or, in the words of fellow physicist Carlo Rovelli, 'a good scientist is never "certain"' (see http://edge.org/responses/what-scientific-concept-would-improve-everybodys-cognitive-toolkit; also Jha, 2011).

Over the past couple of decades, notions of risk and uncertainty have become a topic of increasingly vigorous scientific debate. This debate has been stimulated in particular by another area of extreme complexity—the science of climate change—and by the difficulty of communicating the probabilities of global warming to mass media which crave simplicity and certainty (see, for example, Brown et al., 2013; Friedman et al., 2009). Where Haldane presented the realm of uncertainty as a horizon to be steadily conquered by the advance of scientific knowledge, scholars now stress that uncertainty is itself a part of science that cannot necessarily be removed—'reducing uncertainty is often not possible or necessary, and this is not a barrier to using scientific knowledge...Researchers can incorporate uncertainty into calculations or work around it' (Brown et al., 2013, p. 12). In the fields of society and politics, indeed, scholars such as Ulrich Beck see risk as the defining character of our late modern age (Beck, 1992, 2009).

Uncertainty from Chernobyl to Fukushima

Uncertainty lies at the core of the nuclear dilemma, as the Chernobyl Forum's report makes abundantly clear. To sketch the problem briefly: most knowledge of the effects of radiation on human health is still based on long-term studies of the survivors of the Hiroshima and Nagasaki bombings, who were exposed for very short periods to extremely high levels of radiation. There is no scientific consensus about the appropriate way of extrapolating this knowledge to people who are exposed to much lower levels of radiation over a long period of time. The Hiroshima and Nagasaki studies focused on external radiation, and provide very little information on the effects of internal radiation (caused by ingesting or inhaling radioactive materials), an issue of great importance in the contexts of Chernobyl and Fukushima.

Many scientists adopt the 'linear non-threshold' hypothesis, which assumes that there is no absolutely safe level of exposure to radiation, but that risk is proportional to the level of exposure. This approach is not universally accepted, though. Some argue that there is a threshold below which radiation is safe, or even that low levels of radiation can be beneficial to health. There is good evidence of increased cancer risks from protracted exposure to x and y (gamma) radiation above 100 millisieverts (mSv) (Brenner et al., 2003), but controversies continue about the general risk from exposures below 100 mSv per year. All experts agree that the impact varies greatly according to type of radiation, the nature of the radioactive substances involved, the age and gender of those exposed, and the nature of the exposure. Unborn babies are particularly vulnerable, and other people may need particular protection because (for example) they may already have received higher than normal doses of radiation from medical treatments, etc. Reflecting the need to protect particularly vulnerable groups, the international basic safety standards for the general public define the maximum permissible exposure to ionising radiation as '1 millisievert per year, or in special circumstances up to 5 mSv per year provided that the average over five consecutive years does not exceed 1mSv' (IAEA, n.d.).

Exposure to high levels of radiation is known to impair immunity to infection and increase the risk of leukaemia, certain sorts of solid cancers, cataracts and probably also heart disease and stroke. But all of these health problems already exist in the human population and may be caused by combinations of many factors. The effects often take many years or even many decades to become visible. There is generally no direct way of identifying which cancers or other diseases are caused by radiation. Cause and effect can only be estimated by observing patterns of disease; and when low levels of radiation are spread over large populations, it may be extremely difficult to separate disease caused by radiation from disease caused by other factors. One significant exception is childhood thyroid cancer. This can be caused by ingesting radioactive iodine, and is very rare in the general population, so a sharp rise in childhood thyroid cancer like the one which followed the Chernobyl disaster can confidently be identified as a result of exposure to radiation.

Faced with the challenging nexus of problems surrounding radiation, scientists can respond in either of two ways. They can conduct empirical research, looking closely at affected populations, measuring levels of radiation in the human body and observing unexpected signs of ill-health; or they can conduct probabilistic forecasting, combining knowledge of radiation levels and existing hypotheses about the likely affects of exposure to estimate likely health effects on a particular population.

In the case of Chernobyl, the Russian, Belarus and Ukrainian scientists who responded first to the disaster used empirical research and direct observation to draw conclusions about the human consequences. The Center for Radiation Medicine in Minsk, for example, collected very large amounts of data on children from the most affected areas, while the independent Institute of Radiation Safety in Belarus (Belrad) collected a mass of information on levels of radioactive cesium-137 in foodstuffs and the human body (Kuchinskaya, 2007). Other large-scale studies were also conducted by international groups, including the Japanese Sasakawa Foundation, which from 1991 to 1996 sponsored the largest international study of the effects of the disaster on the health of children (UNSCEAR, 2000, p. 495).

These empirical studies documented a sharp rise in thyroid cancer amongst children in areas most exposed to radiation, and some studies also suggested impaired thyroid function even in children who did not develop cancer. Increases in other solid cancers, and health problems like anaemia, and an increase in the malformation of foetuses were noted in highly contaminated areas (Lazjuk et al., 1997; Lomat et al., 1997; Quastel et al., 1997; Yamamoto et al., 1999). More recent studies have also suggested a connection between radiation and raised leukaemia levels in workers who were involved in the post-Chernobyl clean-up (Zablotska et al., 2012). But the early results were complex and sometimes conflicting, and it proved difficult to confirm the links between increased radiation and the observed health problems. It was generally impossible to collect data on individual exposures to radiation, which would have helped to clarify causal relationships. Besides, in the complex social conditions that accompanied the break-up of the Soviet Union, rates of cancer were rising rapidly even in areas with little exposure to the Chernobyl disaster.

In 2000, the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) published a survey of the existing empirical research. This stated that no direct link had been established between the Chernobyl disaster and health problems except for cases of acute radiation sickness suffered by some emergency workers and cases of childhood thyroid cancer in the wider population (UNSCEAR, 2000). The logic behind UNSCEARs conclusions is puzzling. A number of the scientific studies which UNSCEAR itself cites *did* indicate other likely health problems, including increased levels of certain foetal abnormalities, and of anaemia, endocrine disorders, digestive diseases, tonsilitis, adenoiditis and impaired thyroid function in exposed children (see Box 1). Subsequent research has reinforced some of the early findings—for example, findings of a relationship between low-dose radiation, bladder cancer and the pre-cancerous bladder disorder that has come to be known as 'Chernobyl cystitis' (see Yamamoto et al., 1999; Romanenko et al., 2009). The UNSCEAR report recommended further follow up research, but, apparently dismissing the findings of several of the research papers it had just cited, concluded:

> …apart from the substantial increase in thyroid cancer after childhood exposure observed in Belarus, in the Russian Federation and in Ukraine, there is no evidence of major public health impact related to ionizing radiation 14 years after the Chernobyl accident. No increases in overall cancer incidence and mortality that could be associated with radiation exposure have been found. (UNSCEAR, 2000, p. 516)

The publication of the UNSCEAR report coincided with a fundamental shift in the paradigm used to assess the consequences on the Chernobyl disaster: a shift from direct observation of effects towards much greater reliance on probabilistic modelling—the approach used by the Chernobyl Forum report of 2005. As a result, many of the existing large-scale epidemiological studies were wound back. Olga Kuchinskaya points out that this shift was influenced by political and economic changes in Belarus and Ukraine. With the collapse of the Soviet Union and the introduction of new market systems, funding was no longer available to continue

Box 1
Samples of the Interpretations of Research Findings Given in the 2000 UNSCEAR Report

Original Research Finding	*UNSCEAR Interpretation/Conclusion*
Lomat et al., 1997 *Comparative study found unusually high levels of gastritis, anaemia and tonsillitis amongst children in highly irradiated Gomel area, and suggested that these were caused by a complex of factors of which radiation was one:* 'The highest levels of radiation exposure occurred among children of the Gomel region. These children were found to have the highest incidences of gastro-intestinal, endocrine, and hematopoietic diseases as well as an increased incidence of thyroid cancer...We emphasise that the findings described in this paper... cannot be ascribed *only* to radiation. The roles of improved surveillance of population and psychosocial as well as adverse nutritional and other environmental factors *must also be evaluated*' (pp. 1531–1532, emphasis added).	Describes the Lomat study as attributing the health problems to causes *other than* radiation: 'The authors concluded that the increases were *most probably due to psycho-social, lifestyle, diet and increased medical surveillance* and suggested that further analyses would be needed to establish aetiological factors' (p. 511, emphasis added). UNSCEAR concludes: 'With the exception of the increased risk of thyroid cancer in those exposed at young ages, *no somatic disorder or immunological defect* could be associated with ionizing radiation caused by the Chernobyl accident' (p. 512).
Quastel et al., 1997 *Found evidence of damage to thyroids (other than thyroid cancer) in girls from Chernobyl contaminated regions who had migrated to Israel.* 'TSH serum levels were significantly greater ($p < 0.02$) for girls from high-exposure regions, although these values were within normal limits. Our working hypothesis is that the observed increases in TSH *represent physiologic and homeostatic response to past radiation damage to the thyroids of some of the children examined*' (p. 1525, emphasis added).	After citing the Quastel article, with others, the report concludes: 'Other than the occurrence of thyroid nodules in workers and in children, which is unrelated to radiation exposure, *there has been no evidence of thyroid abnormalities* in affected populations following the Chernobyl accident' (p. 510, emphasis added).
Lazjuk et al., 1997 *Compared abnormalities in all legally aborted (pre-27 week) foetuses in a highly contaminated area and in Minsk City. Found a notably higher increase in certain malformations of foetuses (but not of Down's Syndrome) in the highly contaminated area. The authors warn of need for caution in interpreting results, particularly because individual radiation doses were unknown, but write:* 'Results of our analysis are *consistent with the hypothesis that ionizing radiation released during the Chernobyl accident may have placed fetuses and neonates at risk for congenital malformations*. Epidemiological studies are now required to determine whether a mother's radiation dose correlates with congenital malformations in her children' (p. 255, emphasis added).	UNSCEAR summarises this study as follows: 'The studies conducted on all legal medical abortions from 1982 to 1994 revealed increased rates of polydacty, limb reduction and multiple malformation in highly contaminated areas...The city of Minsk was used as a control, and spina bifida, polydacty, multiple malformations, and Down's syndrome were found to have increased. *No changes in birth defects over time could be related to exposure to ionizing radiation*' (p. 512, emphasis added).

the mass studies that had been undertaken in the first years after the Chernobyl disaster, and an alternative approach to disaster management, focusing less on the direct effects of radiation and more on general development projects, was introduced (Kuchinskaya, 2007, pp. 135–140; see also Kuchinskaya, 2013).

Growing reliance on statistical modelling also reflected global trends in the scientific approach to uncertainty. Confronted by extremely complex and unpredictable issues, such as the impact of human activity on the global climate or the risk of new pandemic diseases, scientists were making increasing use of statistical techniques of probabilistic prediction, and developing ever-more sophisticated methods of statistical model-building. These techniques are very similar to those used by economists to model trends in the complex and chaotic world of the global economy (Palmer and Hardaker, 2011, p. 4682).

The 2005 Chernobyl Forum report noted that twenty-eight emergency responders were known to have died from acute radiation caused by the Chernobyl disaster, and also that around 4000 children had developed thyroid cancer, though the number of deaths was small, because this cancer is quite treatable. But the Forum agreed with UNSCEAR in dismissing the results of empirical studies that had attributed other cancer and non-cancer deaths to the disaster. So, rather than attempting to measure these numbers through further empirical observation, the Chernobyl Forum adopted the quite different approach of extrapolating from existing knowledge of the effects of radiation (derived primarily from Hiroshima and Nagasaki) and using statistical modelling techniques to estimate the likely number of excess deaths that *might be expected* to be caused by the disaster over the long term.

The conclusions generated by the Chernobyl Forum's modelling were extremely tentative: so tentative, indeed, that they have been interpreted in very different ways by those who quote them. They predict that the small expected percentage increase in morbidity amongst people receiving relatively high exposures 'might eventually represent up to four thousand fatal cancers', and amongst 'the 5 million people residing in other "contaminated" areas, the doses... are expected to make a difference of less than one per cent in cancer mortality'. On the other hand, epidemiological studies of the contaminated areas 'have not provided clear and convincing evidence of a radiation-induced increase in general population mortality' (Chernobyl Forum, 2006, pp. 15–16). This can be, and has been, interpreted either as a conclusion that there may be up to 4,000 additional deaths, or that there may be an uncertain but larger number of additional deaths, or that there is no evidence of any increase in deaths in the general population: all of which only adds to already abundant uncertainty surrounding the effects of long-term exposure to radiation on human health.

The Forum report was much less tentative when it came to identifying the core of the Chernobyl problem. This was firmly identified as lying in the minds, attitudes and behaviour of the local people:

> [T]he mental health impact of Chernobyl is the largest public health problem unleashed by the accident to date. Psychological distress arising from the accident and its aftermath has had a profound impact on individual and

> community behaviour. Populations in affected areas exhibit strongly negative attitudes in self-assessments of health and well-being and a strong sense of lack of control over their own lives. Associated with these perceptions is an exaggerated sense of the dangers to health of exposure to radiation... Added to exaggerated or misplaced health fears, a sense of victimisation and dependence created by government social protection policies is widespread in affected areas... This dependency culture that has developed over the last two decades is a major barrier to the region's recovery. (Chernobyl Forum, 2006, pp. 36–37)

The diagnosis of the problem led naturally to a recommendation for reduced government welfare benefits, schemes to promote local enterprise, and a campaign to overcome the scientific ignorance of the population.

> Innovative ways need to be developed to increase knowledge about how to live safely in environments that have suffered radioactive contamination, as well as to reassure people who live in areas where radiation exposure is too low to pose any real threat to health and well-being...Governments also need to clarify to the public, with the assistance of credible international agencies, that many areas previously considered to be at risk are in fact safe for habitation. (Chernobyl Forum, 2006, pp. 53–54)

From about 2000 onwards, the effort to educate the population did include programs which sent international experts into highly affected areas of Ukraine and Belarus to interact more closely with local populations. The two major EU-funded projects—the ETHOS (1996–2001) and CORE (2003–2008) projects—defined their aims as being to develop a more 'bottom-up' approach to the problems of local residents (for example, Lochard, 2013). But, as Kuchinskaya notes of CORE, these projects were also part of the strategy of shifting the focus away from radiation and towards general community development. They therefore tended to sideline the detailed empirical knowledge of the disaster collected by local scientists, and contributed to a environment in which radiation was made socially invisible:

> …the context of sustainable development projects provides limited context for the discussion of radiation protection measures, such as measuring radiation levels in produce; it excludes meaningful discussions related to health and bodies of laypeople: the meetings and interactions I observed provided no opportunities to meaningfully bring up and articulate possible health effects of radiation. (Kuchinskaya, 2007, p. 257)

Though the Chernobyl Forum report recommended the continuation of a range of health monitoring programs, it emphasised the importance of making these 'well-targeted' and 'cost-effective', and was cautious in its proposals for further empirical research. For example, the report notes that there may be increased future deaths from solid cancers amongst those exposed to high radiation, but that 'the feasibility and informativeness of studies [of solid cancers] should...be carefully evaluated before they are started' (Chernobyl Forum, 2006, p. 47).

The Chernobyl Forum estimates of mortality were criticised by scholars including Alexey Yablokov of the Russian Academy of Science and Belrad's father-and-son scientific team of Vassili and Alexey Nesterenko, who drew attention to an implicit conflict of interest in the Chernobyl Forum's research: the IAEA (which played a central role in the Forum) has a mission to promote the civilian use of nuclear power, and a 1959 agreement between the IAEA and the World Health Organization acknowledges the right of the IAEA to take the lead in this field (Broinowski, 2013,; Greene, 2012; Yablokov et al., 2009). Contrary to the Chernobyl Forum report, Yablokov and the Nesterenkos argued that almost one million people had died prematurely as a result of exposure to radiation from Chernobyl (Yablokov et al., 2009). Their assessment, though, was then fiercely criticised by some commentators both within and outside the former Soviet Union, who condemned it for being based on a biased use of sources including non-scientific data (Balonov, 2012; Jargin, 2010). Responses to these criticisms have been published both by the original authors and by other scientists (see Mousseau and Møller, 2013; Yablokov and Nesterenko, 2010). Meanwhile, other researchers had generated further estimates of Chernobyl health effects, some suggesting figures higher than the Chernobyl Forum forecasts, but well below the Yablokov and the Nesterenko figures (for example, Cardis et al., 2006). The controversy continues.

At the time of the March 2011 Fukushima disaster, then, the uncertainties about the impact of radiation on human health were as great as they had been at the time of the 1986 Chernobyl accident. These uncertainties were compounded by failures to collect and communicate accurate information about radiation levels immediately after the Fukushima explosions and meltdowns. In the words of Yamashita Shunichi and Suzuki Shinichi, the two scientists appointed by the Japanese government to lead the response to the health challenges of Fukushima: 'unfortunately, the calculation and prediction of the concentration of radioactive materials in the air, the radioactive dose, and other measurements immediately after the accident could not be performed due to insufficient information on the source of emission...' (Yamashita and Suzuki, 2013, p. 130). As another scientific study notes, 'information on early internal radiation doses in Fukushima after the nuclear power plant accident on March 11, 2011 is quite limited due to initial organisational difficulties, high background radiation and contamination of radiation measuring devices' (Matsuda, 2013, p. 663).

It is tempting to conclude that the one thing we have learnt from Fukushima is the fact that we learnt nothing from Chernobyl; but perhaps the real problem is the selective way in which the lessons of Chernobyl have been applied in Fukushima.

Modelling Fukushima

One concept which *was* almost instantly transferred from Chernobyl to Fukushima was scepticism about the use of epidemiological research into the health effects of radiation. The mass of empirical health data collected in Belarus and Ukraine had clearly not been sufficient to persuade UNSCEAR and the Chernobyl Forum that there were observable links between radiation exposure and any health effects other than acute radiation sickness and childhood thyroid cancer. Since average exposure levels were generally assumed to be much lower in Fukushima than they had been in Chernobyl, many scientists quickly concluded that epidemiological health studies in Fukushima were unlikely to produce persuasive evidence of radiation effects. As Richard Wakefield, editor of the *Journal of Radiological Protection*, wrote soon after the disaster:

> …undoubtedly, there will be epidemiological studies of the emergency workers and of the public living around the Fukushima Dai-ichi site. However, it needs to be appreciated that the statistical power of these studies is likely to be low... Even studies of the much greater collective dose received by the Chernobyl 'liquidators' have not produced clear findings. Unless the magnitude and range of doses received by the public living around Fukushima Dai-ichi NPS has been seriously underestimated, the prospect of finding radiation-related effects in studies of those exposed in the environment is unlikely to be better... (Wakefield, 2011, p. 174)

The Japanese national government and the Fukushima Prefectural government have created large-scale epidemiological studies to monitor the long-term health of Fukushima citizens. The Fukushima Prefecture Health Management Survey was launched in June 2011. It consists of five main elements: a questionnaire directed at the prefecture's two million inhabitants, designed to track their movements following the disaster so as to estimate individual radiation exposures; and four long-term projects to monitor various aspects of the health of the population (Yasumura et al., 2012). But, as the senior director of the study, Yamashita Shunichi, was quick to make clear, he does not expect it to find any physical effects from the accident: 'I do not think there will be any direct effect of the radiation for the population. The doses are too small' (Meyer and Yamashita, 2011). The main purpose of the survey, therefore, is 'to alleviate residents' concerns about radiation' (Fukushima Medical University, 2011; see also Iwata et al., 2012).

This sceptical approach to observational research is in sharp contrast to the positive emphasis on statistical modelling as a means of predicting likely health effects. Probabilistic modelling is used in two steps—first, to estimate human exposure to radiation in Fukushima, and then to estimate the impact that these levels of exposure may have on health. The first step has been attempted by the Fukushima Health Management Survey team in cooperation with Japan's National Institute of Radiological Science (NIRS) and, separately, by the World Health Organization. The WHO has also used its radiation estimates as the basis for a statistical forecast of health effects.

To understand and assess the implications of the important and widely quoted Fukushima NIRS and WHO studies, we need to consider three issues which are conceptually distinct, but which, in a confusing post-disaster world, often become intertwined. The first is the issue of accuracy. Predictions generated by statistical modelling differ depending on the sophistication of the models and the quality of the data fed into them. This difference between accurate and inaccurate prediction is a problem of the *quality of knowledge*, and is the problem that underlies much controversy that surrounds both Chernobyl and Fukushima. But it is also important to look closely at two other, less widely discussed problems of probabilistic prediction, which affect both the Chernobyl Forum report and recent forecasts about the human impact of the Fukushima disaster.

The second problem is an issue not of quality but of the *nature of knowledge*. High quality probabilistic models may be very good at answering certain important questions; but they may also be inherently incapable of answering others. Probabilistic modelling takes a bird's eye view of phenomena. It turns the gritty substance of everyday life into abstract variables that can be handled in mathematical terms. This transformation generates universalising predictive power, but does so at the cost of losing what Kuchinskaya (quoting a Belarus-based scientist) calls 'intimate knowledge': detailed, bottom-up knowledge of the particular circumstances of specific local environments and the groups of people who live there (Kuchinskaya, 2007, p. 112).

A third problem (arising from the second) is the issue of the *over-extrapolation of knowledge*: in other words, the problem of assuming that one form of knowledge provides the answers to questions that it is intrinsically incapable of addressing. Problems of over-extrapolation can occur when people draw unwarranted global conclusions from detailed local knowledge; but they can also arise when globalised big-picture knowledge is assumed to provide all the answers to local, everyday life problems. Unjustified interpretations and extrapolations of statistical forecasting are crucial to many of the controversies surrounding the Fukushima disaster today, and are particularly important in explaining the disjuncture between international scientific discourse on the disaster and the everyday uncertainties of local residents.

The Quality of Knowledge

To explore the intertwined problems of the quality, nature and extrapolation of scientific knowledge in Fukushima, we need to look more closely at the major national (Fukushima Prefecture/NIRS) and international (WHO) modelling of the disaster so far. From the second half of 2011, the Fukushima Prefectural authorities distributed questionnaires to the two million inhabitants of the prefecture, asking them to detail their movements in the days immediately after the March 2011 accident. On the basis of the survey results, an NIRS computer program was used to develop a model of eighteen likely evacuation paths. These were superimposed on Japanese government data about local radiation levels, creating estimates of exposure to external radiation for the first four months after the accident.

The first estimates were produced for the highly affected Sōsō area (including the towns of Sōma, Namie and Iitate), and initially the highest dose received by any member of the general public (excluding radiation workers) was estimated to be 19 mSv, though this was later revised upward 23 and then to 25 mSv (Akahane et al., 2013; *Asahi Shimbun*, 13 June 2013; Institut de Radioprotection et de Sûreté Nucléare, 2012, p. 169; Sakai, 2013). The results produced by the end of 2013 suggested that only 146 members of the general public had been exposed to doses over 10 mSv in the four months after the accident, indicating that the effects of the disaster had been much smaller than at first feared (Fukushima Medical University, 2013).

But the NIRS model, for all its mathematical sophistication, embodies a range of problems that limit the accuracy of its predictions. It looks only at external radiation, entirely excluding the crucial question of internal radiation caused by inhaling irradiated particles or eating irradiated food, and it only considers radiation exposure up to 11 July 2011, excluding the high continuing levels of exposure which many local people have experienced ever since. The Institute also lacked accurate radiation figures for the first three days after the accident (when the highest doses are likely to have been received), so their figures for these days are based on computer simulations.

Besides, the response rate for the Fukushima Prefectural survey, which provides essential information for the estimation of individual exposure rates, was just 23.6 per cent overall, and even in highly affected Sōsō region less than 45 per cent of residents responded (Fukushima Medical University, 2013). The survey itself relied on people's very uncertain memories of their movements several months earlier, during a time of great stress and confusion. Respondents filling in forms in October or November 2011 were expected, for example, to remember where they had been, and whether they had been indoors or outdoors, for every three-hour period of each day six months earlier (Fukushima Prefecture/Fukushima Medical University, 2011).

Although the information collected by this survey obviously provides some indications about likely exposure levels, it is self-evidently not capable of telling us the actual highest radiation dose received by anyone during the four months after the disaster, for several reasons. More than half of the most vulnerable people are missing from the survey, and since the sample who did respond is self-selected, we have no way of being confident that it is representative. The doses modelled by the NIRS system are underestimates, because they exclude internal radiation, and they are only approximate estimates even of external radiation. The official data on external radiation has been questioned by local residents, many of whom conduct their own radiation monitoring, and are well aware that a distance of ten or twenty meters can make a major difference to the reading. The figures used in the modelling exercise were provided by radiation monitoring equipment operated by Japan's Ministry of Education, Culture, Science, Sports and Technology (MEXT). Some Fukushima citizens express concern that these underestimate the problem, because measuring equipment has been known to be placed on solid concrete pillars which partially shield it from radiation. In certain cases, too, decontamination efforts have been particularly thorough in the areas immediately surrounding the government's radiation monitoring posts, making the radiation levels recorded there unrealistically low. Citizen monitoring of radiation levels is reported to find levels on average 10–30 per cent higher than MEXT monitoring (Tanji, 2013).

Unlike the Fukushima Prefecture/NIRS model, the World Health Organization's 2012 preliminary dose estimation tries to put external and internal radiation together into an overall model of exposure. It provides estimates of radiation exposure in broad bands, with the estimates being 10–50 mSv over the year from late March 2011 for the population of the most highly exposed area (WHO, 2012). These figures are not derived from survey data, but are simply based on available Japanese government measurements of radiation levels in particular areas. Building on this estimate of radiation, the organisation's 2013 health risk assessment goes on to model potential human effects of radiation, predicting some health problems including slight increases in cancer levels, while suggesting that these problems will not be major or widespread (WHO, 2013).

The WHO study concludes that, for infants exposed to radiation in the most highly affected area (by which they apparently mean the area around Namie town) there might be a 7 per cent increase in the lifetime risk of leukaemia amongst males. Amongst females exposed as infants in the same area, there a 70 per cent increase in the risk of thyroid cancer, a 6 per cent increase in the risk of breast cancer risk and a 4 per cent increase in the risk of other solid cancers amongst females. In the next most affected area, the health risks would be half this level, and in a wider area of eastern Fukushima, including the cities of Fukushima, Koriyama, Nihonmatsu and Tamura they would be one quarter to one-third of this level. Since the underlying cancer rates are not high, and thyroid cancer is rare, these estimates suggest some cause for concern in the most affected areas, but do not translate into large numbers of affected people (WHO, 2013, pp. 8–9).

Although the WHO's predictive model is more comprehensive than the one produced by Japan's NIRS, there are still reasons to raise questions about the quality of its prediction. For example, the WHO study explicitly excludes exposure to radiation received within the 20 kilometre exclusion zone, because the report's authors lacked the necessary data and assumed that people in this zone had quickly been evacuated (WHO, 2013, pp. 37, 42). But press reports indicate that there were sixty-three households still living within the 20 kilometre zone five weeks after the accident, and some of those who were soon evacuated faced compound levels of exposure: in the case of one primary school, for example, children 'gathered in the grounds of the school which is just over 10 km away from the [nuclear] plant, and then fled to Tsushima District of Namie, which was later hit by the radioactive plume' (Akiba, 2012, pp. 3–4; *Hokkaido Shimbun*, 21 April 2011).

The WHO creates four possible scenarios to assess the health risks to the disaster response workers at the Fukushima No. 1 plant, but their data on workers' radiation levels was provided by the plant's operator TEPCO, and this also raises questions of accuracy. Four months after the WHO report was released, TEPCO announced revised estimates of radiation to the thyroid glands of workers. The number of workers who had been exposed to thyroid doses of over 100 mSv after the accident, which had until then been given as 178 (with a maximum individual reading of 11,800 mSv) now jumped to 1973 (Oiwa and Toshio, 2013). Other dose records are known to be incomplete: most notoriously, workers employed by Build-Up, one of hundreds of sub-sub-contractors engaged in the disaster response at the plant, did not have their radiation properly monitored because they were instructed to cover their dosimeters with radiation-blocking lead shields before entering the plant (Sato et al., 2012).

Almost all the studies of radiation conducted so far (including the WHO survey) have focused on radioactive iodine and caesium, but research suggests that other substances including plutonium and strontium were released by the explosion. One group of scientists has studied soil samples from several spots fairly close to the Fukushima plant, and found that 'very low' levels of plutonium had been released by the accident. They observe that this 'may also have health physical implications because the inhalation of such plutonium-rich particles may result in high local dose delivery to the lung tissue' and point out that their findings 'demonstrate the need for more detailed investigations on plutonium distribution and speciation in order to assess potential radiological consequences for the public' (Schneider et al., 2012).

The Nature of Knowledge

Like all conceptual models, then, the Fukushima Prefecture/NIRS and WHO studies are imperfect representations of the real world. Their accuracy is inevitably limited by the state of theoretical knowledge on radiation and by lacunae in data. Of course, the fact that they are imperfect does not make them useless. They provide important information for understanding and responding to the ongoing disaster, but serious problems arise if they are mistaken for actual representations of the real world, and (as we shall see) this mistake is too often made not only by media and public commentators, but also by some scientific experts themselves. Just as importantly, though, the statistical models represent a particular *form* of knowledge which is, by its very nature, limited in its capacity to deal with the real-life, intimate dilemmas faced by populations exposed to raised levels of radiation.

Consider, for example, the findings of the WHO health risk assessment for Fukushima. On the face of it, these should be quite reassuring for local residents. But these findings are hypothetical projections of average dose rates; and people in eastern Fukushima do not live in an average world. The level of external radiation is not spread evenly like a carpet all over the area. It is a mosaic where levels may vary from very low to unusually high from one side of the street to the other, or from one rice paddy to the next. Most people, most of the time, do not know what level of radiation they are standing in.

If you attempt to live a relatively normal life in affected areas of Fukushima Prefecture, you are unlikely to know whether or not the food you are eating contains radioactive substances. Food bought in shops rarely tells you where in Japan it was produced. One supermarket chain, which has a few outlets in Fukushima City, proudly proclaims that it tests all its fruit and vegetables for radiation:

the majority do not. Government food testing has been spotty and sporadic. Independent testing shows that many locally produced foodstuffs contain no discernible level of radiation, but that some contain high levels (CRMS, 2014). Individuals do not necessarily eat the 'standard Japanese diet' on which the WHO predictions are modelled. If they have the misfortune to unwittingly consume a series of different items with high radiation levels over the course of several meals, they risk possible exposure to substantial internal radiation.

For those who move through the landscape of Fukushima, internal and external doses of radiation from various isotopes are not neatly separated in the way that they are in academic research papers. They happen all at once. Many people, having been exposed to unknown doses of radiation (possibly including radiation from plutonium) within the 20-kilometre evacuation zone immediately after the accident, now live as refugees in areas of Fukushima where they continue to traverse a mosaic of wildly varying radiation levels, eat food that may be irradiated at unknown levels, and breath air whose dust may come from one of the public car parks where soil was still, in late 2013, contaminated with radiation at extremely high levels (CRMS, 2014). In their unending search for responses to the problem, the victims of the disaster may well find it more meaningful to have detailed, intimate knowledge about the levels of radioactivity in their food, their neighbourhood and their own bodies, and about observed changes in their own and their family's health, than to have a globalised estimates of overall radiation levels and potential morbidity levels spread over populations of hundreds of thousands or even millions.

Mistaking Model for Reality: Ignorance Revisited

These problems of the quality and nature of knowledge are compounded by the problem of extrapolation. Scientists grappling with uncertainty often express dismay at the difficulty of communicating their knowledge to the public. In the area of climate change particularly, the fact that science cannot make firm predictions about the precise level and local consequences of global warming, but can only provide estimates of probabilities, is often exploited by sceptics as a basis for questioning the idea of human-generated climate change as a whole (Brown et al., 2013).

But in the case of Fukushima, the opposite dynamic is at work: rather than questioning and expressing scepticism about the predictive models of radiation exposures or health effects, media reports often mistakenly quote these models as though they were empirical descriptions of what is actually happening, or has already happened, in the real world. So, for example, the results Fukushima Prefecture/NIRS survey of radiation levels are conveyed to the global public through media reports like the *Nature* article which tells us that, in the worst affected areas, 'the highest recorded dose was 23 mSv, well below the acute 100 mSv exposure linked to a slight risk in cancer' (Brumfiel and Fuyuno, 2012, p. 139). Disturbingly, this assertion seems to be derived from public statements by the Fukushima Prefecture Health Management Survey's senior director Yamashita Shunichi, who used the 'maximum' finding of 23 mSv exposure to reassure his audience about possible health risks, arguing that: ‘there is no clear evidence of cancer-causing effects below 100 millisieverts a year, so from this result it is hard to imagine that there could be any health effects’ (*Iwate Nippō*, 21 February 2012).

The same encouraging message was given in a separate press conference by Sakai Kazuo, Director of the NIRS Research Center for Radiation Protection. Sakai deployed attractive PowerPoint slides to contrast the ‘maximum’ Fukushima exposure level of ‘20 mSv plus’ with the 100 mSv a year level, below which he too claims no health effects are to be expected. His conclusion was that ‘the total level of radiation received by Fukushima citizens is not at a level that causes concern’ and, categorically, that it ‘will not cause health effects’ (Sakai, 2013). His message is echoed by Abel J. Gonzalez, a member of UNSCEAR and vice-president of the International Commission on Radiological Protection (ICRP). In a public letter to the citizens of Fukushima and Japan, published on the home page of the Japanese prime minister and cabinet on 30 July 2013, Gonzalez explains:

> ...*in summary, international experts have concluded that this catastrophic accident has providentially resulted in very small radiation doses in general and therefore no discernible health effect...* You can therefore reinitiate your normal lives. (Gonzalez, 2013, emphasis in original)

Needless to say, for the citizens Ōkuma, Futaba and other towns in the exclusion zone, ‘reinitiating normal life’ would mean returning to homes within a few kilometres of the ruined and still dangerously leaking nuclear plant, and to localities which according to the Japanese government’s own predictions will continue to experience radiation levels of over 100 mSv per year until 2017 and of over 50 mSv per year well into the 2020s (Ōkuma Machi Yakuba, 2012).

The flaws in the reassurances from Yamashita, Sakai, Gonzalez and others are obvious. The 23 mSv ‘maximum exposure’ figure (later to be revised upward to 25 mSv) was not ‘the highest recorded dose’ received by anyone in the affected area. It is a predictive estimate, based on an incomplete survey of the population and on data whose accuracy is uncertain. It is also a partial estimate: an estimate of *external* radiation only. If internal radiation had been included, the figure is very likely to have been higher. Even more importantly, Yamashita and Sakai compare an estimate of the radiation dose received in the *first four months after the accident only* with a supposedly ‘safe’ level of 100 mSv *per year*. People still living in eastern Fukushima continued to be exposed to raised levels of radiation for the rest of the year and beyond, and the Fukushima Prefecture/NIRS study gives us no estimate of their annual exposure, though we can be certain that it was well above their exposure for the March–July period. Equally, the state of scientific knowledge does not allow us to say that radiation exposure between 10 and 100 mSv a year ‘will not have health effects’. We can only say that there are divergent scientific views on the chance that it will affect people’s health.

Not even the more comprehensive WHO study provides us with an accurate grasp of ‘the total level of radiation received by Fukushima citizens’. Its predictions tell us something about the possible range of risks, but the simple fact is that we do not know whether Fukushima accident has or has not affected the health of local people. We will not know this for decades. Even ten or twenty years from now, our knowledge will almost certainly be incomplete.

Brian Wynne, whose reflections on science and everyday life draw on his studies of Welsh and Cumbrian farms affected by Chernobyl fallout, makes an important distinction between 'risk', 'uncertainty' and 'ignorance'. 'Risk' exists where an event may or may not occur, but the odds of its occurring are relatively well known; 'uncertainty' is the situation where the broad parameters of a risk are understood but science is not (or not yet) capable of accurately assessing the odds. But 'ignorance' takes problem one step deeper. In a situation of uncertainty, we are aware that there are variables we cannot predict; but in a situation of ignorance, we do not know what it is that we don't know (Wynne, 1992, pp. 114–117).

Particularly in very complex natural events, there are almost inevitably some variables that may influence the outcome of event, but which, so far, nobody has recognised as being relevant. Ignorance, in this sense, is something more than an unfortunate but temporary oversight. It is, Wynne argues, 'not a pathology of science but a necessary feature of structured investigation' (Wynne, 1992, p. 115). The intrinsic nature of modern science is that it creates an artificial world in which a limited number of variables are included, allowing the researcher to focus on a particular selected conundrum. 'Scientists can define a risk, or uncertainties, only by artificially "freezing" a surrounding context which may or may not be this way in real life situations' (Wynne, 1992, p. 116). It is only within this artificially 'frozen' world that scientists can create the order needed to generate clear conclusions about causal relationships in nature, but 'the resultant knowledge is therefore conditional knowledge, depending on whether these pre-analytical assumptions might turn out to be valid' (Wynne, 1992, p. 116).

'Not knowing what we don't know' is therefore not a bad thing in itself; ignorance has positive uses. But it becomes dangerous if researchers or public commentators forget or deny their own ignorance, and over-confidently apply results obtained in the artificially controlled world of the academic study to the complex world of everyday life, where a much more tangled nexus of unforeseen circumstances may be at work. Good quality predictive modelling of the potential effects of the disaster is essential to provide a framework for interpreting any observed changes that may occur in the environment or human health over the years to come. But science risks losing its grip on reality if the predictive results of the modelling are treated as substitutes for, or equivalents of, careful and intimate observation of radiation levels and their effects; and (as we shall see) events have already shown that confident predictions can prove to stand on shaky ground.

Embodying Indeterminacy: Anxiety, Iodine and Thyroid Cancer

In addition to 'risk', 'uncertainty' and 'ignorance', Brian Wynne's lexicon of incertitude includes fourth crucial category—'indeterminacy'. This is a notion that goes beyond 'uncertainty' because it emphasises the human–nature interaction that lies at the heart of issues like climate change or radiation releases. 'Indeterminacy' brings human choices and human behaviour firmly into the equation (Wynne, 1992, pp.117–119). The notion of indeterminacy is particularly important in understanding the unease that surrounds Fukushima. The difficulty of predicting the health effects of the Fukushima accident is not just a result of limited knowledge about the ways that radioactive isotopes react with human tissue. It is also a result of the unpredictable nature of human actions. How individuals in Fukushima will be affected by radiation depends on social context, on policy decisions and on choices taken by international organisations, the Japanese authorities, TEPCO and the local residents themselves.

The Chernobyl Forum report of 2005 provided a firm set of recommendations about the right approach for dealing with the disaster. The greatest public health problem was the mental stress associated with unnecessary fears of radiation. A core element of the response should therefore be public education campaigns to overcome public ignorance and reassure local residents of their safety. These lessons were very rapidly applied in Fukushima. The message that 'there is no immediate threat to health', or more sweepingly that the disaster would have no health effects at all, was repeated to the residents of Fukushima by leading national and international experts, starting from the days immediately after the accident.

This determination to prevent anxiety had unfortunate effects. It was undoubtedly one factor behind the decision, encouraged by Yamashita Shunichi and experts from the NIRS, not to distribute stable iodine tablets (which can reduce the risk of thyroid cancer) to residents of areas affected by the disaster. The only residents given these tablets were the people of Miharu town, whose local government decided to provide tablets on their own initiative despite instructions from the Prefectural government not to do so (R. Hasegawa, 2013, p. 28). Yamashita, who is well known for his detailed research on thyroid cancer in Chernobyl, later acknowledged that he had underestimated the severity of the Fukushima radiation releases: 'I thought that Japanese nuclear reactors would have had proper filters to remove [radioactive] iodine. It never occurred to me that the pollution would spread so widely' (quoted in *Asahi Shimbun*, 8 November 2013). A prominent NIRS scientist involved in the decision not to distribute iodine tablets has also since expressed second thoughts about the decision: 'when I think back on it now, we should have got people to take them' (Akashi Makoto, quoted in *Asahi Shimbun*, 10 November 2013).

Despite this experience, the leading scientific institutions have continued to use the results of probabilistic modelling as a basis for arguing that there is no public health risk, and that the only real problem is the fear arising from residents' ignorance of science. Sakai Kazuo of the NIRS echoes the Chernobyl Forum report by telling his Japanese audience that there is no risk to public health from the disaster except anxiety, which stems from local people's 'lack of accurate information' about radiation, while Abel Gonzalez of UNSCEAR tells the citizens of Fukushima that the only significant health effect of the disaster is 'on mental and social well-being, related to the enormous impact of the earthquake, tsunami and nuclear accident and the fear and stigma related to radiation exposure' (Gonzalez, 2013; Sakai, 2013).

Yamashita Shinichi takes the Chernobyl lesson one step further. His message is not just that public ignorance and anxiety about radiation constitute the major public health problem. He also publicly argues that, while radiation levels under 100 mSv a year are not a cause of cancer, anxiety is: 'Stress is not good at all for people who are subjected to radiation. Besides, mental-state stress also suppresses the immune system and therefore may promote some cancer and non-cancer diseases' (Meyer and Yamashita, 2012). So, speaking to residents of some of the worst affected areas of Fukushima less than two weeks after the tsunami and nuclear disaster, and shortly after he had advised the authorities against distributing iodine pills to the public, Yamashita exhorted his audience to keep smiling because 'radiation does not affect those who are smiling. It does affect those who are gloomy. This has been clearly demonstrated in animal experiments' (quoted in *Tokyo Shimbun*, 30 December 2011, p. 20). The largest scientific study of the subject so far has found no association between mental state and the chance of contracting or of surviving cancer (see Nakaya, 2010).

The Fukushima Health Management Survey was expected play a central role in overcoming local residents' excessive anxiety by showing that there were no negative health effects from the disaster, but by May 2014, its study of 287,056 people who were aged less than eighteen at the time of the accident had found ninety cases of suspected or confirmed thyroid cancer—thirty-two in boys and fifty-eight in girls (Aoki, 2013; Fukushima Prefecture/Fukushima Medical University, 2014, p. 4). All of these young people have either already undergone surgery or will be operated on soon. So far, fifty cases have been confirmed and only one of the suspected cases has proved to be non-cancerous. If all or most of the remaining thirty-nine cases are confirmed, this would represent a pre-adult thyroid cancer around 60 to 150 times the previously recorded Japanese level (a level of around 310 per million population, as opposed to the two to five per million population found in the prefectures with the best cancer records between 2002 and 2007—see Kokuritsu Gan Kenkyū Sentā, 2013, part 3).

The Japanese authorities and some international experts insist that this unexpectedly high number of cases cannot be a result of the Fukushima accident, and must simply reflect the fact that screening with very sensitive equipment is showing up small tumours which would not normally be felt by patients or reported to doctors at this stage (Aoki, 2013; Hooper, 2013). There are some grounds for this argument. An earlier study of adult women in Japan found that screening programmes substantially increased the recorded number of thyroid cancer cases, though the increase in this case was around 11-fold, rather than the 60- to 150-fold increase currently being found in Fukushima today (Ishida et al., 1988; Kokuritsu Gan Kenkyū Sentā, 2013, Part 3). The only firm conclusion at the moment must be that we do not know whether the Fukushima thyroid cancer cases are a direct result of the nuclear accident, but that the level is high enough to raise serious concern, and that careful studies will be needed over the years to come.

The thyroid cancer cases do not only draw attention to unresolved questions about the quality of predictions on the effects of the disaster. They are also an illustration of what happens when indeterminacy goes beyond the realms of scientific debate and modelling, and enters the infinitely complex world of everyday human life. Given the experience of Chernobyl, it would have been unthinkably negligent of the Japanese government not to have carried out thyroid screening; and, once cancers started to be found, operations inevitably followed. There nothing in the least ignorant or irrational about the parents of the cancer patients choosing to have their child undergo surgery, even though the surgery and treatment is likely to affect the patients' health for the rest of their lives. The anxiety felt by those children and their parents is clearly not a reflection of ignorance or irrational fear, and cannot be removed by public exhortations to stop worrying and reinitiate one's normal life. Whether or not the cancers prove to have been the consequence of the Fukushima disaster, the lives and health of the children have been changed forever by the consequence of their diagnosis and treatment. When everyday life is exposed to massive and destabilising disruptions like the Fukushima disaster, uncertainty itself ceases to be a purely abstract or mental phenomenon, and begins to have consequences that may be tangible, physical, and very painful.

From Uncertainty to Incredulity

In addition to the many environmental differences that distinguish the Fukushima from the Chernobyl disaster, there is a crucial social difference. The citizens of Fukushima have access to the Internet, and with it, to a mass of information—of wildly varying quality—about the effects of radiation. This includes high quality scientific debate about the possible effects of the disaster, very good monitoring data about local radiation levels conducted by citizens groups, and the usual swarms of partisan websites which often convey wildly inaccurate rumour of all types. In this environment, endlessly repeating that message that 'there will be no (or no immediate) health effects' has not had the intended effects.

Far from making Fukushima residents less anxious and more confident about the future, this strategy has contributed to a profound sense of public scepticism towards any information provided by government bodies or by international organisations such as the IAEA, UNSCEAR and WHO. A chorus of voices testifies to Fukushima residents' alienation from official scientific pronouncements, and to the sense of an unbridgeable gap between expert information and lived local experience:

> Immediately after the accident, I believed it when we were told that there would be no immediate threat to health, so I didn't escape from the radiation then. Since then I have realised that you can't trust the government safety standard or what the government says. Female evacuee from Fukushima to Niigata Prefecture. (quoted in *Niigata Nippō*, 4 December 2013)

> The first news wasn't about radiation warnings. They said it's OK, that there was no problem, radiation wasn't spreading. Only later I found out what was really

happening, and I couldn't believe that there was a point where radiation was so high... We have to be strong and believe that we can live here, but we don't know what to believe. Nemoto Ichidori, Fukushima farmer. (quoted in Keshet, 2013)

The only way for the officials, cabinet ministers and bureaucrats to convince and persuade the local people that it is safe to return is for them to come and experience life in the village for themselves, to prove by experiment with their own bodies that one can live in safety and peace of mind in our village; unless they turn their own experience into data, we will not be able to believe anything they tell us. Shoji Masahiko, evacuee from the Iitate district. (Shoji, 2013)

It's impossible for them [the Japanese national authorities] to regain our trust by carrying on the way they are at present, deciding policy without consulting local people. Baba Tamotsu, Mayor of Namie Town. (quoted in *Niigata Nippō*, 4 December 2013)

A government survey conducted six months after the disaster found that the number of Japanese people who said that they 'trusted' or 'somewhat trusted' scientists had fallen by over 20 percentage points (Ishizuka, 2012). By the beginning of 2014, soul-searching in the Japanese scientific establishment was leading to public statements like this, from the science bureau chief of the conservative daily *Yomiuri*:

Whether they like it or not, scientists must dirty their hands with real life. Scientists must turn their eyes towards daily life, not just towards research results, and they must communicate things that are not 100% safe or certain. (S. Hasegawa, 2014)

Studying the interaction between scientific experts and the Welsh and Cumbrian farmers affected by fallout from Chernobyl, Brian Wynn observed a fundamental clash of cultures

…between the taken-for-granted scientific culture of prediction and control, and the farmers' culture in which lack of control was taken for granted over many environmental and surrounding factors in farm management decisions. The farmers... valued adaptability and flexibility, as part of their identity and practical knowledge. The scientific experts ignored or misunderstood the multidimensional complexity of this lay public's problem-domain, and thus made different assumptions about its controllability. (Wynne, 1996b, p. 67; see also Wynne, 1996a)

He concludes by calling for scientists who address the environmental effects of radiation to listen to and respect local residents' intimate knowledge of their own natural and social environment, rather than one-sidedly imposing their culture of 'prediction and control' on the wider population. That conclusion has powerful resonance for the situation in Fukushima today.

Towards a New Approach to Science and Everyday Life in Fukushima

Some Japanese scientists are already responding in new ways to the challenges posed by the disaster, and in Fukushima today, spaces for a more fruitful dialogue between scientific experts and local residents are being opened up by the emergence of a range of fascinating 'citizen science' projects initiated by the people actually exposed to the effects of radiation from the disaster. Japan has a long tradition of citizen science, going back at least to the immediate post-war period (Nakayama, 1991, pp. 14–25). In the aftermath of the 3/11 disaster, this tradition has come to the fore again, and is playing a crucial role in providing detailed on-the-ground studies of the effects of the disaster.

One example is the network of Citizens' Radioactivity Measuring Stations (CRMS), whose work is in part inspired by the history of organisations like Belrad which emerged following the Chernobyl disaster. In Fukushima, the fear, uncertainty and poor communications surrounding the nuclear disaster has created a desperate demand for reliable radiation measurements, and led to a new wave of citizen's action. The first of the Fukushima Citizen's Radioactivity Measuring Station was opened four months after the accident, on 17 July 2011, and moved to its current home in a small shopping arcade in the city centre in October of the same year. This was followed by the creation of measuring stations in the nearby cities of Koriyama (opened in August 2011) and Tamura (October 2011), and further afield. At the end of 2013, there were nine centres in the CRMS network, eight in Fukushima Prefecture (Fukushima City, Tamura, Koriyama, Sukagawa, Nihonmatsu, Minami Sōma and Tōwa) and one in the Tokyo district of Setagaya. In addition to the CRMS network, there are many other locally initiated radiation measuring centres which have been created by a wide variety of citizens' groups, non-profit organisations and private companies throughout Japan from Hokkaido in the north to Kumamoto in the south.

The CRMS network has a very small core of full-time staff, and relies overwhelmingly on the work of volunteers, most of whom had no prior knowledge of nuclear science. They include housewives, retired people and others who have trained themselves in the knowledge needed to operate the network's measurement equipment which, in the case of the Fukushima City branch, includes a whole body counter imported from Belarus. CRMS organisers and volunteers have acquired their understanding of radiation science by attending seminars organised by scientists and NGOs after the disaster, and seeking out knowledge from the Internet and from specialist books and articles.

The CRMS tests food and other material (water, soil samples, etc) brought in by farmers and consumers for radioactive caesium, and publishes the results of all its tests online. Anyone can make an appointment at its Fukushima City branch for a whole body measurement, which checks the body for irradiation with caesium and iodine. CRMS charges a small fee for its measurements, and arranges follow-up medical consultations for those receiving whole body measurements. Their testing has produced results that are in some ways reassuring—the irradiation of the foodstuffs and human bodies that they have tested is less massive and widespread than some observers (including some members of CRMS itself) initially feared. But it is extremely variable. Many samples show no signs of radiation at all, but high levels of radiation have been found in various foodstuffs (including mushroom, persimmons, game meat, etc.), and even in late 2013 soil from some public spaces in Fukushima was showing extremely high radiation levels (CRMS, 2014). The CRMS does not claim that its measurement results are comprehensive (particularly because they do not contain data on possible irradiation by substances like plutonium and strontium), and it does not make general pronouncements on the risks to human health. Its aim is simply to provide trustworthy information on which residents can rely as they decide how best to live their lives in an uncertain environment.

In some cases, the work of these citizens' groups has also led to fruitful collaborations between Fukushima residents and those Japanese academic scientists who are willing to listen closely to the voices and experiences of residents. The CRMS in the little rural town of Tōwa (population 7,000) for example, is embedded in a farmers' non-profit organisation which had been set up before the Fukushima disaster to try to promote local organic farming. In Tōwa, which lies just outside the exclusion zone, farmers have joined a series of collaborative projects with academic institutions including Niigata University and Tokyo University of Agriculture and Technology to test soil and crops and develop ways of growing radiation-free food (Nonaka, 2014).

Their work is just part of a mass of post-disaster research which is shedding important new light on the interaction of radioactivity with the environment. The most important findings from this research include a growing recognition of the complexity of this interaction. Levels of radiation vary greatly from one spot to the next not only because of topography but also because of differences of microclimate and soil structure, the flow of water and nature of plant growth. This highlights the need for detailed radiation mapping, which, in the case of Tōwa, has been carried out by local residents themselves with advice from scientific experts.

The amount of radiation absorbed varies not only between different plant species, but also between different strains of the same species. Experiments in growing different rice strains in the same paddy field, for example, show that some strains absorb more than twice as much radioactive caesium as others (Kojima et al., 2013). Besides, different plants interact in different ways with soils and fertilisers. After the Fukushima disaster, large scale projects were started to plant sunflowers in some of the worst affected areas, because experiments in Chernobyl had found that sunflowers were effective in absorbing radiation, and so removing it from soil and groundwater (Singh and Tripathi, 2007, pp. 193–194; Slodkowski and Nakao, 2011). But the Fukushima project ended in failure: the make-up of the soils of eastern Fukushima is quite different from that of the peaty soils of Chernobyl, and therefore the interaction of plants, soil and radiation is also different (Matsumura et al., 2013; *Ibaraki Shimbun*, 17 June 2014). Experiences from Fukushima highlight the fact that responses to radiation exposure cannot simply be transferred from one place to another, but need to be targeted to the specific environment of the affected community. This finding again reminds us of the need for careful empirical study of the effects of an event like the Fukushima disaster, and of the dangers of simply imposing predictive models derived from one event to another occurring in very different places.

Meanwhile, the alternative approach to decontamination favoured by the Japanese government—removal of the irradiated topsoil—has also encountered major difficulties. The most obvious is the unresolved problem of finding a place to store up to 100 million cubic metres of radioactive soil which will eventually be removed in the decontamination process (Mori, 2011). Meanwhile, although soil removal temporarily lowers radiation levels, research in Tōwa has shown that radiation accumulated in leaf litter in the mountain forests is constantly washed down into farm fields by the flow of water, raising levels of radioactivity again. Scientists are now experimenting with more complex and holistic approaches to address the radioactive contamination of the forests which form such a central part of Japan's rural bio-system; but it will take years if not decades for the results of these experiments to be known (Nonaka, 2014, pp. 96–101).

The CRMS volunteers and groups like the Tōwa farmers show astonishing determination and persistence in acquiring complex scientific information and combining it with their own knowledge of local environments. Their lives were thrown into complete chaos by the disaster—as well as losing most of their crops, Tōwa farmers opened their doors to provide the first place of refuge for thousands of people fleeing from the neighbouring town of Namie—and yet they have managed to acquire an impressive understanding of radiation science and embark on ambitious research ventures to rescue their communities from oblivion. The work of these citizen scientists has received some outside funding, but it has not received the official recognition it deserves. In the words of one CRMS worker whom I interviewed: 'the government doesn't really pay any attention to our findings. They think we're just a bunch of amateurs.'

Conclusions

The experiences of Fukushima, as we have seen, highlight the gap between 'uncertainty' as it is understood in the realm of contemporary scientific discourse, and the lived experience of indeterminacy confronted by those whose everyday lives are affected by nuclear disaster. The failure to recognise and reflect on this gap has resulted in damaging failures of communication and understanding between some of the scientists responsible for the response to the disaster, and has compounded the difficulties faced by the people of the affected areas. As recent research from Fukushima emphasised, the environmental impacts of radiation are immensely complex and deeply embedded in the unique structures of local biospheres. This makes the practice of assessing the likely affects of a nuclear disaster by extrapolating from abstract predictive models particularly problematic.

This problem is not simply an issue of 'scientists versus non-scientists', for there are scientists in Japan and elsewhere who express their own sense of frustration and even anger at way in which science has been deployed in the response to the Fukushima disaster (for example, Koide, 2011; Oshikawa, 2013). The fundamental problem is a matter of epistemology, or more precisely of epistemological distance. The Kafkaesque sense of the absurd that permeates much of life in Fukushima today has its origins, far less in the 'ignorance' of the citizenry, than in a particular view of science as a self-contained and authoritative realm floating above the messy, contingent world of everyday life. In place of the much-reiterated denial of risk, there is a need for a rethinking of the relationship between science and mundane existence, and between 'expert' and 'citizen' knowledge.

New conversations and partnerships, and better responses to the needs of Fukushima's residents, are possible. Scientific experts can learn (and some have learned) to listen to voices from outside the discipline, to acknowledge the value of 'intimate knowledge', and understand the local sources of human anxiety. To further this dialogue, science itself needs to open its doors to everyday life: to breathe the air, to walk the parks, and to touch the grass of Fukushima.

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