Malformation of True Bug (Heteroptera): a Phenotype Field Study on the Possible Influence of Artificial Low-Level Radioactivity

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The results of extensive field studies on the malformation of Western European true bugs (Heteroptera) are reviewed. More than 16,000 individuals were collected over two decades, and subjected to detailed visual inspection. Various types of disturbances were found and illustrated in detail. Depending on country, region, as well as local influences, severe disturbances and high degrees of malformation were noticed, especially in the sphere of nuclear-power installations in Switzerland (Aargau), France (La Hague), and Germany (Gundremmingen). Malformation reached values as high as 22 and 30% for morphological (MD) and total disturbance (TD), respectively. This is far above the values expected for natural populations (*ca.* 1%) or those determined for true bugs living in biotopes considered as relatively 'intact' (1–3%). A detailed chi-square test of the malformation data obtained for 650 true bugs from 13 collection sites near the nuclear-reprocessing plant La Hague showed a highly significant correlation ($p = 0.003$) between malformation and wind exposure/local topography. Similar observations were made for other study sites. Currently, our data are best rationalized by assuming a direct influence between the release of anthropogenic radionuclides such as tritium (^{3}H), carbon-14 (^{14}C), or iodine-131 (^{131}I), constantly emitted by nuclear-power and nuclear-reprocessing plants, as well as by Chernobyl and bomb-testing fallout, which is rich in caesium-137 (^{137}Cs) and other long-lived noxious isotopes that have entered the food chain. The present work supports the growing evidence that low-level radiation, especially in the form of randomly scattered 'hot' α- and β-particles, mainly transported *via* aerosols, puts a heavy burden on the biosphere in general, and on true bugs in particular. These insects could, thus, serve as sensitive 'bio-indicators' for future studies.

1. Introduction. – 1.1. *Retrospective.* I used to work for 25 years as a scientific illustrator[3]) at the Scientific Department of the Natural History Museum of the University of Zurich, Switzerland. Professor *Hans Burla*, then head of the department, was one of the first geneticists working with *Drosophila subobscura*. In his research, he mutated flies by exposing them to the mutagenic agent ethyl methanesulfonate (EMS; **1**), and I had the assignment to draw the mutated flies, one of which was called '*quasimodo*' [1]. I was very impressed with these mutated flies and continued painting them on my own. Another branch at the institute was investigating taxonomic issues by studying flies. Thus, by illustrating several monographs on Drosophilidae and Leucophenga [2], I learned how to draw flies precisely [3], either their whole body or parts thereof, and also how to catch, authenticate, and prepare insects for collections.

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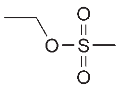
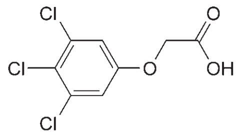
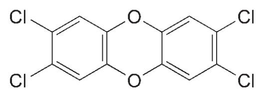

EMS (**1**)


Agent Orange (**2**)


TCDD (**3**)

In 1963, I had the opportunity to study six months at the marine biological institute *Acquario* in Naples, Italy. Under the supervision of the renowned scientific illustrator *Ilona Richter*, I learned how to draw and paint living specimens of sea snails (nudibranchia). I also illustrated a monograph on Ostracoda (seed shrimp) [4]. The beauty of these small sea creatures impressed me immensely, and later, when I had the chance to work also at the marine biological institute in Banyuls sur mer, France, as well as at different marine biological institutes in the South Pacific, I thought that I had found my destiny. However, marriage and children kept me in Switzerland, where I was looking for new specimens to paint. Then, in 1968, I discovered the true bugs (*Heteroptera*), which marked the beginning of a great love.

In the 1960s and 1970s, ecological awareness was in its infant shoes, despite worldwide industrial and military pollution, including radioactive fallout from bomb testings[4]) [5], the effect of chemical weapons such as the herbicide and defoliant *Agent Orange* (=3,4,5-trichlorophenoxyacetic acid; **2**) in Vietnam [6], or severe chemical incidents as, *e.g.*, the release of TCDD (=2,3,7,8-tetrachlorodibenzodioxin; **3**) in Seveso, Italy [7]. Sensing that Nature was more and more endangered, I gradually developed the notion that mutated laboratory flies were physically rendered *prototypes* of our destructive behavior, materializing the future of Nature.

Later, in 1985, I started to paint a new series of mutated laboratory flies. The geneticists at the Zoological Institute of the University of Zurich were still mutating flies at the time, but, in contrary to the 1960s, they were now exposing them to X-rays instead of poisoning them chemically. Then, at 1.24 a.m. of April 26, 1986, the bell for a new era was tolled: while I was painting mutated flies of the species *Musca domestica*, the catastrophe in Chernobyl happened. Radioactivity was spread all over Europe (*Fig. 1*) [8], including Switzerland (*Fig. 2*) [9], and as many a mother, I was preoccupied by the choice of food I would give to my children. This situation, as bad as it was, generated the notion that all living beings in areas contaminated by the radioactive cloud were now *in a situation comparable to that of laboratory flies* exposed to radioactivity. I imagined that my beloved true bugs, especially those living in contaminated areas, could suffer body deformations. I discussed this disturbing idea with Professor *Ralph Nöthiger*, geneticist at the University of Zurich, but he was convinced that the radiation in Europe was far too low to have such an effect on Heteroptera or other creatures.

[4]) Between 1945 and 1996, a total of 2,398 nuclear weapons were brought to explosion by the U.S.A., the former U.S.S.R., U.K., France, and China (Pakistan and India not being counted) [5]. This corresponds to an overall destructive power of 520 Mt (megatons) of the chemical explosive TNT (=2,4,6-trinitrotoluene), or to *ca.* 40,000 Hiroshima bombs of 13 kt each! From 1945–1980, most tests were conducted above ground (in the atmosphere).

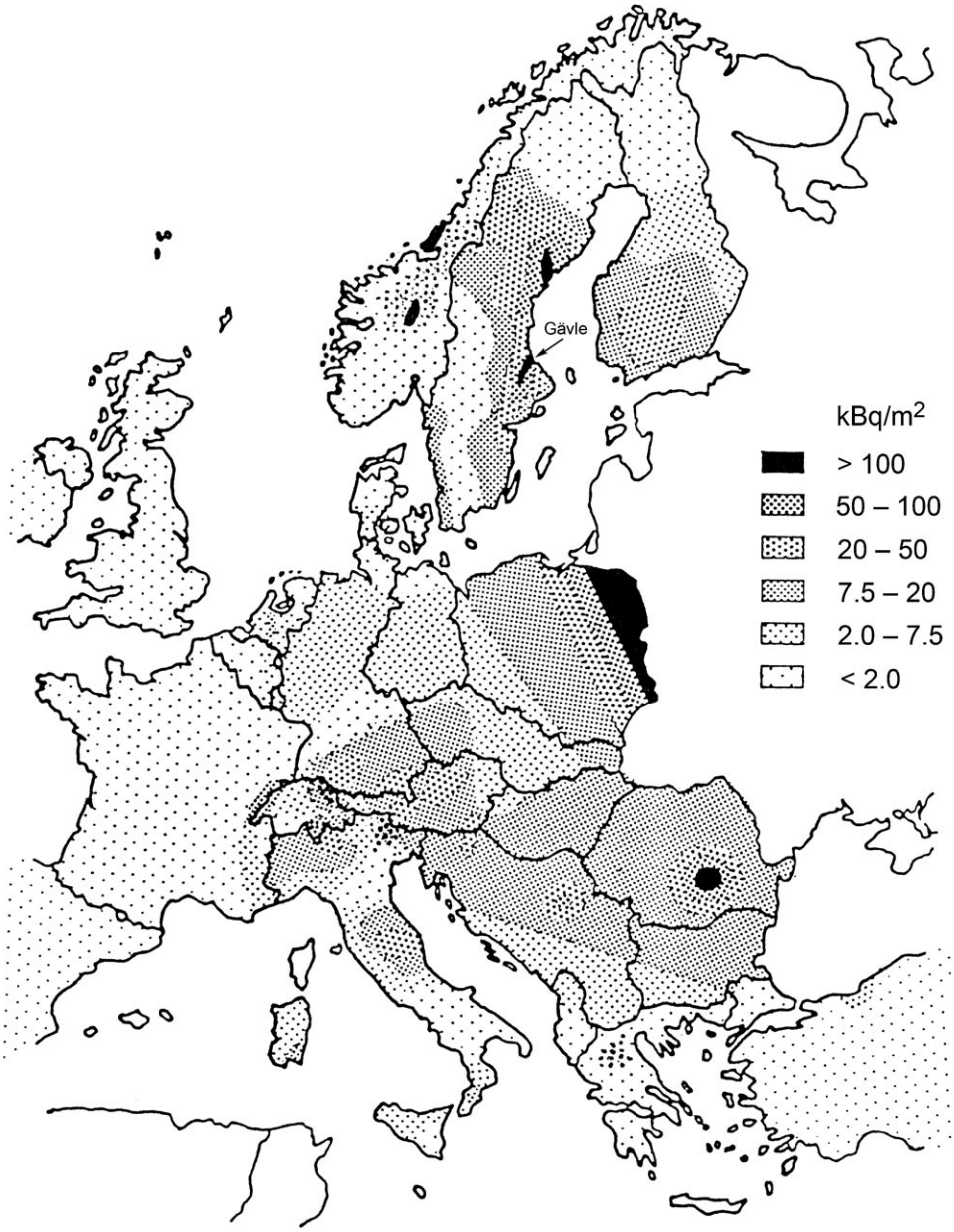


Fig. 1. *Soil contamination in Europe by ^{137}Cs and ^{134}Cs from the Chernobyl cloud.* Extrapolated data of summer 1986. Adapted from [8].

This assumption, however, did not comfort me, and I decided to study the new generations of true bugs, *i.e.*, the offspring of parents 'irradiated' by the Chernobyl cloud. Only now had I found my true destiny: a long, but exciting, journey over two

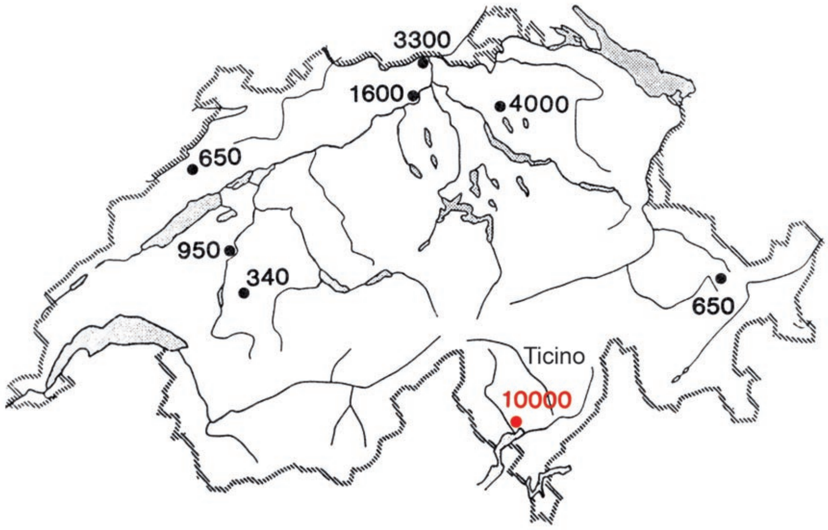


Fig. 2. *Rain-deposited* ^{137}Cs *in Switzerland from the Chernobyl cloud*. Data based on the total rainfall during April 25–Mai 30, 1986. The radioactive cloud swept over the country on April 30. Adapted from [9].

decades began. From 1986–2007, I systematically investigated the morphological appearance (phenotype) of various true-bug species all over the world (*Table 1*), starting in Gävle, Sweden (*Fig. 1*), which was exposed to high loads of artificial radionuclides from the destructive Chernobyl cloud.

Today, when I look back, I realize that I have collected more than 16,000 true bugs (*Table 1* and *Fig. 3*), performing field studies on all continents, except for Australia. Over the years, I have painted more than 300 individual true bugs in detail, and true to scale, and many of these paintings have been shown in international art galleries and museums. As far as I know, no comparable study has ever been performed on Heteroptera or related species. In this paper, I will, thus, provide an overview on my results on Heteroptera, the ultimate goal being to address the delicate question whether or not even low degrees of artificial radiation negatively affects these fascinating, yet sensitive insects. If the answers to this tricky question is 'yes', then Heteroptera could be viewed as sensitive 'bio-indicators' of our environment at a microscopic level.

1.2. *Heteroptera*. True bugs, belonging to the phylum Arthropoda, are insects in the order Hemiptera, suborder Heteroptera [10]. Worldwide, *ca*. 40,000 different true-bug species are known, with some 30 families being recorded in Europe. One hallmark of the arthropods is their outer skeleton, whose size (*ca*. 1–30 mm) is well-correlated with the insect's host range [11]. True bugs have developed a trachea system for breathing. Their bodies are divided into well-defined segments: *i*) the head, *ii*) the breast, which carries the wings and consists of three segments, and *iii*) the multi-segmented abdomen (*Fig. 4*). Heteroptera are closely related to the cicada (Auchenorrhyncha) and the aphids (Sternorrhyncha). Most true bugs feed on plants, but some bug families, such as

Table 1. *Chronological List of Research Areas and Targets for the Evaluation of True-Bug Phenotypes.* For details, see *Experimental* and text.

Entry	Year	Location	Country	Target	Bugs[a])
1	1971	Tema	Ghana	reference biotope	50
2	1987	Gysinge Österfärnebo Gävle	Sweden	Chernobyl fallout	80
3	1987	Melano Rancate	Switzerland	Chernobyl fallout	60
4	1988	Gösgen Leibstadt	Switzerland	nuclear-power plant	221
5	1989–1998	Sellafield	U.K.	nuclear-reprocessing plant	445
6	1989–1992	Gockhausen Isérables	Switzerland	reference biotope	313
7	1990	Chernobyl: Polesskoje Pripjat Seljony Mys	Ukraine (former U.S.S.R.)	Chernobyl fallout	55[b])
8	1991	Three Mile Island	U.S.A.	nuclear-power plant	409
9	1992–1994	Mouans Sartoux	France	reference biotope	111
10	1992–1995	Sta. Maria	Switzerland	reference biotope	270
11	1992–2003	Villigen (near *PSI*)	Switzerland	nuclear-research laboratory	1863
12	1993–1994	Tubre Bormio	Italy	Chernobyl fallout	299
13	1994–1996	Canton Aargau	Switzerland	nuclear-power plants	2600
14	1993	Correns	France	–	118
15	1994	Bagnols en Forêt St. Maxime	France	–	206
16	1995	Stade Krümmel	Germany	nuclear-power plant	754
17	1997	Nevada	U.S.A.	nuclear-weapon test area	1292
18	1997	Weggis	Switzerland	reference biotope	68
19	1998	Hanford	U.S.A.	nuclear factory	2139
20	1999	Cape de la Hague (Normandy)	France	nuclear-reprocessing plant	650
21	2002–2004	Gundremmingen (Bavaria)	Germany	nuclear-power plant	2900
22	2004	Cu Chi[c])	Vietnam	*Agent Orange*	360
23	2005	Carlow Dundalk	Ireland	reference biotope	131
24	2005	Golfo dulce	Costa Rica	reference biotope	63
25	2006–2007	Entlebuch	Switzerland	reference biotope	910
Total					**16367**

[a]) Total number of bugs collected and analyzed over the time period indicated. [b]) Only a small number of bugs could be collected due to the local radiation. The recommended duration of stay was *ca.* 10 min (Pripjat) and 3 h (Polesskoje, Seljony Mys), depending on the distance to the molten reactor core. [c]) Including other, less-known areas in Vietnam heavily sprayed with Agent Orange (**2**) between 1961 to 1971.

Fig. 3. *Part of the private collection of true bugs collected between 1971 and 2007.* See also *Table 1.*

the assassin bugs (Reduviidae) and fire bugs (Pyrrhocoridae), also feed on small prey or carrion. The most important characteristics that these three orders have in common is their trunk-like suctorial mouthpiece. Bugs have this trunk on the ventral side of their body. It is stretched forward to draw in food. Hair-like cannulae extend from the end of the trunk and are stuck into leaf material or prey. The front wings of leaf bugs are called hemielytrea, because they are semi-hard and often brightly colored, in contrast to the wing tip, which is soft, membranous, and more or less transparent. Another characteristic of Heteroptera are their glands, which, on larvae, are located on the back. From these glands, a liquid can be sprayed as chemical defense.

True bugs belong to a group of insects with an incomplete development, the so-called Hemimetabola. Unlike beetles and butterflies, they do not pupate. The larvae already have a structure similar to that of the adult animals. The growing larvae have to moult at least five times. In temperate regions, true bugs are typically active from April to October, depending on family and species. Many types of bugs spend winter time in different places. The adult insects of several species hide in protected places, for example, among fallen leaves or in the bark of trees. Others spend winter in the egg stage and hatch in spring. A third type may even spend winter as larvae.

Heteroptera live in a variety of habitats. They do not like cold and rainy days. Most bugs feed on plant juices, which they suck from leaves, stems, seeds, or flowers. When a larva (*ca.* 1 mm in size) hatches from the egg, it immediately starts to suck liquid from its host plant with its trunk. Also important is the observation that true bugs live over generations on the same spot. They rarely fly and, if so, then only very short distances, typically a few meters.

1.3. *Radioactivity.* 1.3.1. *Types of Radioactivity.* There are three types of radioactivity: α-, β-, and γ-radiation, all belonging to the class of 'ionizing radiation', *i.e.*,

Fig. 4. *Dorsal* (*a*) *and ventral* (*b*) *views of selected true bugs*. Magnification: 7–10 times. *a*) Watercolor of a squash bug (*Coreus marginatus*; Coreidae) from Polesskoje, Ukraine (1990). *b*) Watercolor of a soft bug (Miridae) from Holmrook, U.K. (1989). © *Cornelia Hesse-Honegger*, Zurich.

radiation that ionizes matter [12]. α- and β-radiation are different kinds of *particle* radiation, set free upon the spontaneous decay of natural or artificial radionuclides. In contrast, γ-radiation as well as X-rays are of purely electromagnetic nature.

α-Radiation consists of charged helium ($^4He^{2+}$) nuclei, *ca.* 5×10^6 eV of energy, which penetrate water or organic matter only on short distance (*ca.* 40 μm). However, when set free *within* an organism, α-particles are extremely dangerous (much more than X-rays), because they locally kill cells irreversibly. β-Radiation consists either of high-energy electrons (β^-) or positrons (β^+). Here, the penetration depth (in organic matter) lies in the millimeter range (skin), the energy being 10^3–10^6 eV, depending on the type of radionuclide. Finally, γ-radiation (present, *e.g.*, as cosmic radiation) covers all types of electromagnetic radiation with energies higher than *ca.* 0.2×10^6 eV. The penetration depth of γ-radiation lies in the centimeter-to-meter range. Examples of α-radionuclides are the natural isotope uranium-238 (^{238}U) and thorium-232 (^{232}Th), or the unnatural plutonium-238 (^{238}Pu). β-Emitting radionuclides are, *e.g.*, the naturally occurring isotopes tritium (^3H) and carbon-14 (^{14}C), or the artificial sulfur-35 (^{35}S), iodine-131 (^{131}I), and cesium-137 (^{137}Cs). Some artificial radionuclides such as cobalt-60 (^{60}Co) often undergo first a β-decay, followed by emission of photons (γ-radiation).

1.3.2. *Accumulation of Radioactivity in Plants and in the Environment*. Unless noted otherwise, the following information was taken from [13][14]. Radionuclides can enter plants either through their roots or leaves. From the Chernobyl incident, we know that lichen, mushrooms, and berries incorporated higher levels of radionuclides compared to most other plants. Because of the accumulation of radioactivity in the food chain [15] and, hence, the danger to humans, those plants could not be used for a long time, and thousands of mammals eating them had to be killed.

The negatively charged root walls and the plant epidermis both bind cationic radionuclides by ion-exchange processes, including strontium-90 (^{90}Sr)[5]), ^{137}Cs, and different barium (Ba) and ruthenium (Ru) isotopes, in varying relative amounts [13] (there on p. 59). Thereby, the anthropogenic ^{137}Cs radionuclide is especially dangerous, because it is related to potassium (^{40}K), and the cells have problems to discriminate between these two elements (in their ionic forms). Note that ^{137}Cs is dumped into water by reprocessing plants, thus finding its way to pastures and grass. Further, mushrooms are known to accumulate Cs and Sr; and trees with leaves accumulate artificial radionuclides of uranium (U), lead (Pb), Cs, and Sr, which are constantly released into the environment, including the Sea [16]. Many of these and other isotopes have long half-lives.

Another critical aspect is the dumping of radioactive ^3H by nuclear-power plants. Tritium is emitted from the volatile-releasing stacks (connected to the pressure chamber of the reactor) into the air and transported *via* aerosols, or they are released into waters, either directly or through small cracks in the cooling system [17], thus entering the hydrological cycle. Positively charged tritium ($^3H^+$) readily exchanges with water to form tritiated water: $^3H^+ + {}^1H_2O \rightleftharpoons {}^1H^+ + {}^3H^1HO$. This water can then be 'smuggled' into cells (cytoplasma), so that tritium enters the plant metabolism, where it is accumulated irreversibly [13] (there on p. 57).

5) Approximately 99% of the environmental ^{90}Sr, which has a half-life of 29 years, comes from the fallout of tested radioactive weapons. The remaining 1% is mostly due to the Chernobyl accident.

Radionuclides are often transported *via* aerosols in the atmosphere. Typical nuclides in aerosols are krypton, either in the form of ^{89}Kr ($\rightarrow$ ^{89}Sr) or ^{90}Kr ($\rightarrow$ ^{90}Rb $\rightarrow$ ^{90}Sr), xenon ($^{137}Xe \rightarrow {}^{137}Cs$), and radium ($^{226}Ra$), the latter being accumulated in the European flora most of all by clover (*Trifolium pratense*). Further, aerosol-transported plutonium (Pu) is known to be readily accumulated by tobacco, and thorium (Th) can be detected in the bark of roots and in the epidermis of leaves.

The artificial plutonium nuclides $Pu^{238-240}$ have been emitted by the nuclear-reprocessing plant Sellafield (U.K.) and dumped into the Irish Sea, entering the food chain by accumulation in algae. Artificial Pu has also been found in bee honey due to worldwide contamination by heavy atom-bomb testing [5] and the dumping of waste from nuclear-power as well as nuclear-reprocessing plants [13] (there on pp. 65–69).

The radionuclides ^{134}Cs, ^{137}Cs, and ^{129}I (derived from ^{131}I), with half-lives of *ca.* 2 years, 30 years, and 15.7 million years, respectively, have been emitted during the accident in Chernobyl in large quantities. These isotopes are mainly responsible for the *long-term contamination* of the ground, especially in the Ukraine and Belarus (former U.S.S.R.), as well as in Europe (*Fig. 1*). Even more than 20 years after Chernobyl, ^{137}Cs can still be identified in many European soils, and has become part of the food chain.

1.3.3. *Effect of Artificial Radioactivity on Animals.* The effects of radioactivity, especially those of X-rays, on mammals (including humans) are well-documented [18]. There is also a large amount of literature on the effect of low-level ionizing radiation on laboratory animals [19]. However, only few publications have been devoted to the effect of artificial radioactivity on organisms living in their specific habitats.

In 1998, *Saura et al.* [20] accidentally hit on an unusually high mutation rate of the lethal factors in the O-chromosomes of *Drosophila subobscura* in Gävle, Sweden (see *Fig. 1*), a place known to be significantly affected by the Chernobyl fallout. There, the genetic load, including both lethals and semilethals, was higher in comparison with those of other European marginal *D. subobscura* populations.

In a long-term study on the effects of radioactivity on animals, *Møller et al.* [21] analyzed thousands of barn swallows (*Hirundo rustica*). By comparing reference populations from intact European biotopes with Chernobyl populations, the authors established a dramatic relationship between radioactivity and morphological abnormality. Thus, while the natural frequency of abnormalities lies typically in the order of 1% [21b], the Chernobyl swallows showed values of 33.5 and 17.8% for nestlings and adults, respectively.

In an extensive laboratory study conducted by the *Emanuel Institute of Biochemical Physics*, Moscow, mice were exposed to external ^{137}Cs low-dose radiation for different periods of time [22]. Generally, a nonlinear dose–effect dependence was observed, with low doses mainly increasing the sensitivity of cells, organs, and organisms to different damaging factors. Thereby, in certain dose ranges, low-level long-time irradiation generally produced *larger* effects than high-level short-time exposure. For these and related phenomena, the term '*Petkau* effect' has been coined [23].

In 1989, I published a provoking article in the renowned Swiss magazine *Das Magazin* [24]. Based on my results, partly published later in a monograph [25] and in more than 20 oral presentations (see, *e.g.*, [26]), I put forward the hypothesis that even low levels of ionizing radiation due to anthropogenic radionuclides, emitted in the vicinity of nuclear-power plants, cause morphological deformations in true bugs and other insects such as grass hoppers or flies (*Fig. 5*).

Fig. 5. *Heavily deformed scorpion fly* (*Panorpa communis*) *from Reuenthal, Switzerland, near the nuclear-power plant Leibstadt* (1988). This watercolor was reproduced on the front cover of the Swiss magazine *Das Magazin* [24]. © *Cornelia Hesse-Honegger*, Zurich.

As a reaction to this article, a severe political debate took place in Switzerland. Therefore, at the *Swiss Federal Institute of Technology* (*ETH*) in Zurich, a dissertation was conducted to unequivocally clarify this issue. In the resulting Ph.D. work of the zoologist *Johannes Jenny* [27], the conclusion was reached that there is no relationship between true-bug deformation and the location of Swiss nuclear-power plants[6]). *Jenny*

[6]) In my opinion, there are several flaws in *Jenny*'s work. First, his conclusion mostly rests on analysis of the abundant, aggressive, and civilization-adapted fire bugs (*Pyrrhocoris apterus*), which are especially prone to mechanical damage. Second, the whole study lacks a clear systematic approach, and important data such as precise collection sites are missing.

observed unusually high degrees of malformation (10–30%), which he claimed to be mainly due to mechanical effects such as injuries from fights.

While writing this article, the *Bundesamt für Strahlenschutz* (*BfS*), *i.e.*, the *German Federal Institute for Radiation Protection*, spread a shocking press release, based on a five-year study performed by the *Deutsche Kinderkrebsregister Mainz* (*DKKR*; to be published), including a total of *ca.* 6,300 children, of which 1,600 had developed some form of cancer. The *BfS* states on December 12, 2007 (see http://www.BfS.de): '*Das Risiko für Kinder unter 5 Jahren, an Leukämie zu erkranken, nimmt zu, je näher ihr Wohnort an einem Kernkraftwerk liegt*'[7]). Notably, the groups of *Körblein* as well as *Viel* had reached similar conclusions already in the 1980s and 1990s [28]. Apart from that, *Körblein* also showed that there is a statistically significant effect between above-ground nuclear-weapon testing and human perinatal mortality [29]. Truly, the debate on the benefits and risks of nuclear power has just begun!

2. Experimental. – 2.1. *Study Areas.* In this paper, the field-study results from 6 out of 25 selected areas will be presented (*Table 1*). These areas include:

- Gysinge (60° 17′ N, 16° 53′ E), Österfärnebo (60° 19′ N, 16° 48′ E), and Gävle (60° 40′ N, 17° 08′ E) in Sweden (*Table 1*, *Entry 2*), which were heavily contaminated by the Chernobyl radioactive cloud (*Fig. 1*);
- the vicinity of the villages of Melano (45° 55′ N, 8° 59′ E) and Rancate (45° 52′ N, 8° 58′ E) in Ticino, Switzerland (*Entry 3*; see also *Fig. 2*), which were contaminated by the Chernobyl cloud as well;
- the rural city of Polesskoje (53 km W/SW), the abandoned town of Pripjat (4 km NW), and Seljony Mys (34 km SE), all situated near the Chernobyl nuclear-power plant (51° 16′ N, 30° 14′ E; *Entry 7*);
- the whole Cantone Aargau, Switzerland (*Entry 13*), the main city being Aarau (47° 23′ N, 8° 03′ E), where there are four nuclear power plants and one nuclear research laboratory, all within short distance (5–28 km);
- Cape de la Hague, Normandy, France (*Entry 20*), with the La Hague nuclear-reprocessing plant (49° 40′ N, 1° 53′ W); and
- the vicinity of the Gundremmingen nuclear-power plant (48° 30′ N, 12° 24′ E), in Bavaria, Germany (*Entry 21*).

2.2. *Selection of Local Collection Sites.* Generally, three different methods were used to determine collection sites: *1*) predetermined map-based intersection points; *2*) randomly selected intersection points within a map section; and *3*) personal choice. For the systematic studies performed in Canton Aargau (*Table 1*, *Entry 13*), standard 10 × 10 km sections, 25 in total, had 15 major intersection points within the border of Aargau, on a regular 1:100,000 map (*Fig. 6,a*). These 15 major intersection points were taken as primary, predetermined study sites. Further, each of the 25 major square sections were divided into 36 subsections, giving rise to a 6 × 6 matrix each, with 25 *internal* intersection points (*Fig. 6,b*). One such internal intersection point each was then chosen by throwing the dice, providing a secondary, random location. For each of

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[7]) In English: '*For children under five, the risk to suffer from leukemia increases the closer they live to a nuclear-power plant*'.

the primary (15) and secondary (25) intersection points, 65 true bugs were then collected within a limited zone of *ca*. 20×20 m, giving rise to a total of $40 \times 65 = 2{,}600$ bugs analyzed individually.

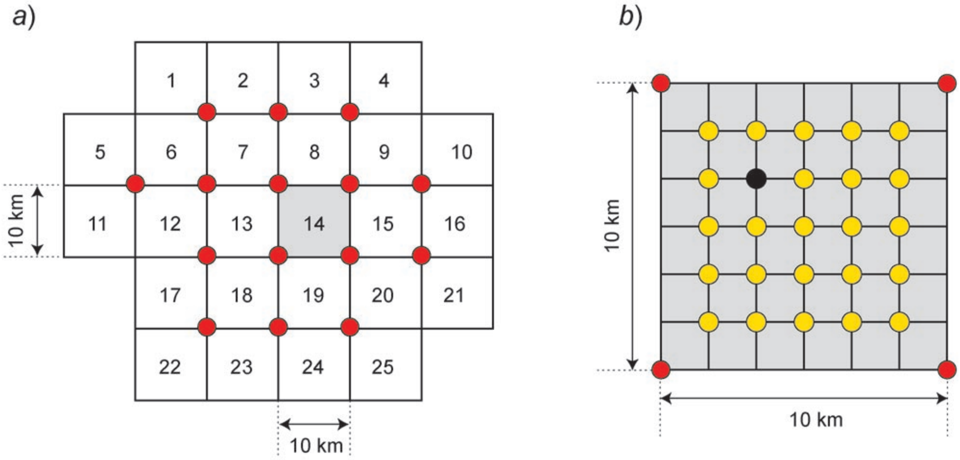

Fig. 6. *Different methods of selecting sites for bug collection in Canton Aargau, Switzerland*. *a*) Geographically predetermined collection sites (red dots) based on all 15 *internal* intersection points of the 10×10 km squares *1–25* needed to cover the whole Canton Aargau. *b*) Each of the main squares *1–25* (as indicated for square *14*) was then subdivided into a 6×6 matrix, with 25 internal intersection points (yellow dots), of which one (black dot) was randomly selected. In total, thus, $15 + 25 = 40$ collection sites were investigated, yielding a data set of 2,600 bugs (65 individuals per site) from 40 collection sites.

2.3. *Collection, Evaluation, and Preparation of True Bugs.* In systematic studies, a total of either 50 or 65 true bugs per location were randomly collected[8]) in the designated study area, in summer time (Mai–September), when it was dry, either in the morning or late afternoon, when being active. To collect this number of bugs typically took 3 h to 1 d. When a bug was found on its host plant, it was trapped by shaking the plant[9]), whereupon it let itself fall into a small, transparent plastic container. The container was quickly covered with a clean paper towel, fixed with a rubber band, and labeled (location and date). The bugs were then killed in a closed container by forcing them to inhale ethyl acetate (AcOEt), which typically took place within minutes.

Each individual true bug was examined within 12 h after collection, and before stiffening (*rigor mortis*). The bugs were scrutinized individually, first from the ventral and then from the dorsal side, under a *Leica MZ16* microscope at a magnification range of 7–80, depending on animal size, using two cold-light sources. Morphological abnormalities in feelers, head (including trunk and eyes), thorax, scutellum, wings, abdomen, legs, and feet were noted separately (*Fig. 7*). Further non-morphological

[8]) Malformation of true bugs usually cannot be detected without the help of a magnifying lens or a microscope.

[9]) During collection, it is important not to make any eye contact with the insects, otherwise they immediately let themself fall onto the ground, where they can no longer be traced.

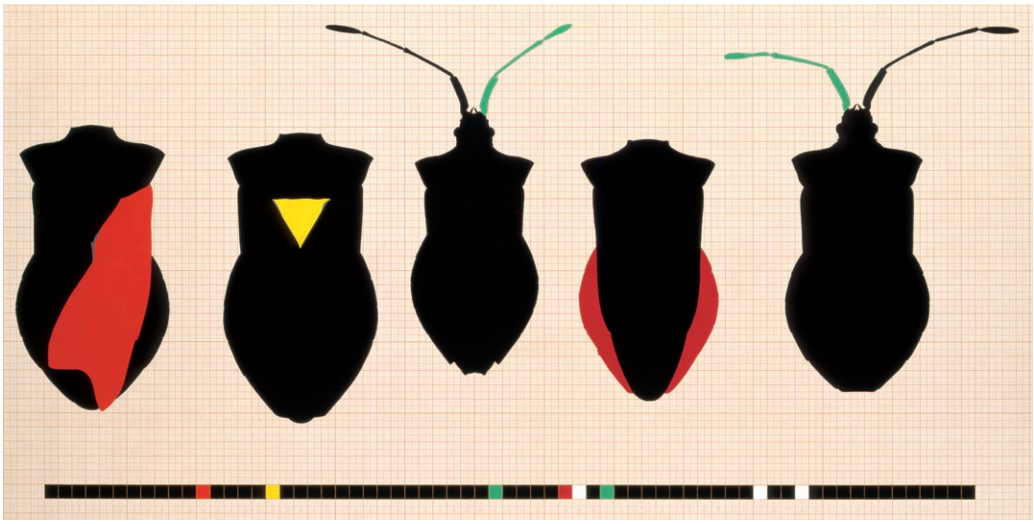

Fig. 7. *Sequence of observed morphological disturbances of randomly collected squash bugs collected near the* Paul Scherrer Institute *in Villigen, Switzerland* (1995; tempera on graph paper). From a total of 67 collected bugs, five were malformed. Color-coded squares: black: healthy, red: wings, yellow: scutellum, green: feelers, dark red: abdomen. The white squares refer to three animals with unusual white or dark patches, but no morphological alterations (not shown). © *Cornelia Hesse-Honegger*, Zurich.

criteria were, *e.g.*, the presence of dark patches or rings, clusters of punctures, unusual pigmentation, or altered texture, *etc.* (see *Table 2*). Blisters, as observed by *Jenny* [27], were not counted as deformations. For statistical analysis and comparison of malformation data, only the most prominent disturbance was counted per animal, even when several disturbances were present.

With the aid of the detailed evaluation scheme shown in *Table 2*, statements can be made not only on a quantitative basis (frequency of malformation), but also on a qualitative level (exact type and severity of abnormality). Finally, the labeled insects were prepared for collection (*Fig. 3*) by standard methods, fixing them with tiny needles, all manipulations being carefully performed with fine tweezers. Each individual bug was given a collection number, matching the corresponding data sheet used for statistical analysis. The data were handled and analyzed with the *Excel* software.

2.4. *Production of Watercolors.* Selected bugs were painted in watercolor, true to scale, by using the internal ruler (in cm) in one of the oculars of the microscope. The insects were first drawn with pencil, all details being exactly measured. When finished, the pencil drawing was transferred with the help of graphite paper to watercolor paper, and finally worked out with brush and paint. Thereby, I painted according to *Paul Cézanne*'s 'Color Perspective'. There is no specific source of light and no shadow, allowing one to simulate the species-typical colors. Notably, larvae had to be painted within a few hours after killing, due to rapid shrinking, in contrast to adult animals, which mostly remained intact, both in terms of shape and color.

Table 2. *Typical Morphological Disturbances Observed in True Bugs*

Body part	Disturbance
Feelers	sections grown together sections in new lengths one section missing boil on the feeler knotted feelers (Miridae)
Head and eyes	asymmetric head disturbed eye(s) eye pigment on head indentations
Thorax	disturbed selvage disturbed little teeth edge to the scutellum disturbed asymmetric disturbed opening for the legs
Wings	crumpled, or bent up and down asymmetric, unequal lengths asymmetric veins
Abdomen	asymmetric disturbance of segment segments grown together segment edge with atypical form or pattern
Legs	too short too thick/thin lack of femur or tibia
Feet	lack of a section one section foot with claws

3. Results and Discussion. – 3.1. *Reference Biotope: Shift in Paradigm.* I have collected and painted true bugs and flies for more than 30 years now. In the years before the Chernobyl accident (1986), I never noticed any significant malformation in these insects. Only after Chernobyl, I started to investigate this issue in more detail, especially after traveling to Sweden in 1987 (*Table 1*, *Entry 2*), where I was shocked by the deformations on true bugs living in areas contaminated by the radioactive cloud. At that time, I was convinced, as most other scientists, that high doses of (artificial) radiation would have a more significant effect on animals than low doses. More and more, however, my results forced me to question this assumption, as later confirmed, in a different context, by *Petkau* and co-workers ('*Petkau* effect') [23], as well as by other scientists [19–22].

Nevertheless, to be able to compare deformation frequencies in true bugs, I needed suitable reference biotopes, *i.e.*, places basically unaffected by man-made sources of pollution such as chemical and nuclear-power plants, dense infrastructure (highways), agriculture, or high-voltage power lines. Despite much effort, only a few places were found that qualified as reference biotopes (see below). A comparison of these study sites is given in *Table 3*.

Table 3. *Selected Studies on Potential Reference Biotopes*

Entry	Location	Country	Year	Bugs collected	Disturbance [%][a])	
					TD	MD
1	Tema	Ghana	1971	50	8.0	0
2	Isérables	Switzerland	1992	265	3.4	1.9
3	Weggis	Switzerland	1997	68	1.5	1.5
4	Golfo dulce	Costa Rica	2005	63	1.6	0
5	Carlow	Ireland	2005	50	4.0	2.0
6	Entlebuch	Switzerland	2007	910	12.7	6.9

[a]) The terms TD and MD refer to total disturbance and morphological disturbance, respectively (see *Experimental*).

Six different reference-biotope study sites were specifically analyzed, where I collected, depending on circumstances, up to 900 bugs. In the case of Tema (Ghana, 5° 38′ N, 0° 0′ E; 1971), which then was still unaffected by 'civilization', and of Golfo dulce (Costa Rica, 8° 39′ N, 83° 15′ W; 2005), at the edge of rainforest near the seashore, there were *no* morphological deformations (MD) found (113 animals investigated in total), and only a small number (1.6%) of other disturbances (OD) were detected in the animals collected in Golfo dulce. According to the literature, mutation frequencies in the range of *ca.* 1% are typical among animals [21] [30]. Therefore, the above two sites were regarded as 'intact' biotopes (at the time).

Next, a total of 383 true bugs from three different places in Switzerland and Ireland were investigated: *a*) in the region of Isérables (46° 10′ N, 7° 15′ E) in Valais (1992), at an altitude of 1100 m above sea level (265 bugs); *b*) in the region of Weggis (47° 2′ N, 8° 26′ E), a beautiful area at the famous lake Lucerne (Vierwaldstättersee) (68 bugs); and *c*) in Carlow (52° 41′ N, 6° 49′ W), Ireland (50 bugs). In all three cases, only few animals ($\leq$2%) showed disturbances.

As another potential reference biotope, I chose the mountainous region of Entlebuch (*ca.* 46° 53′ N/8° 0′ E to 46° 48′ N/7° 56′ E) in Central Switzerland (*Fig. 8*), which had been approved in 2001 by the *UNESCO* (*United Nations Educational, Scientific and Cultural Organization*) as the first *Swiss Biosphere Reserve* (*Fig. 9*). A total of 14 different locations (*Table 4*) were chosen according to topographic criteria, lying within an area of *ca.* 12×16 km. Per study site, 65 true bugs (including cicada) were collected, amounting to a total data set of 910 individual insects.

In *Table 4*, the relative number (in percent) of disturbed true bugs is shown for each of the 14 collection sites in the Entlebuch. The disturbance varied dramatically, ranging from 3 to 23%. Thereby, a qualitative relationship between disturbance and geographical situation in terms of north-wind exposure was observed. This is exemplified in *Fig. 9*, which shows the main valley of Entlebuch, lying in North–South direction. Interestingly, the true bugs form Flühli (*Table 4*, *Entry 5*), Hüttlenen (*Entry 3*), and Südelgraben (*Entry 1*), all lying in the main valley, showed high degrees of malformation (14–23%). In contrast, those in less north-wind-exposed areas, *e.g.*, in a side valley (Chragen; *Entry 10*) or behind the white karst ridge of the Schrattenfluh mountain (Vorderer Hübeli; *Entry 12*), showed lower values (4–6%). This trend was also observed for most of the other sites listed in *Table 4*.

Fig. 8. *A rural valley in Entlebuch, Switzerland*. The photo was taken close to the village Sörenberg (46° 49′ N, 8° 2′ E). This beautiful region was selected in 2001 by the *UNESCO* as the first *Swiss Biosphere Reserve* and was, thus, expected to be a good '*reference biotope*' for true bugs, since there are no (evident) sources of pollution, and because agriculture is performed according to highest ecological standards. Photo by *C. H.-H.* (2007).

Table 4. *Local Geographical Differences in True-Bbug Malformation in the Entlebuch, Switzerland, in Summer 2007*. A total of 14 different sites were investigated, collecting 65 bugs per site, *i.e.*, 910 individuals in total. Collection sites marked bold are located in *Fig. 9*. For a discussion, see text.

Entry	Collection site	Altitude [m]	Wind exposure	TD [%][a])
1	**Südelgraben**	1423	+	23.0
2	Salviden	1375	+	23.0
3	**Hüttlenen**	925	+	21.5
4	Kemmeriboden	1400	+	20.0
5	**Flühli**	890	+	13.8
6	Marbacheregg	890	+	12.3
7	Planalp	1340	–	10.7
8	Husegg	1335	±	7.6
9	Rossweid	1440	±	7.6
10	**Chragen**	1040	–	6.1
11	Salvideli	1250	–	4.6
12	**Vorderer Hübeli**	1315	–	4.6
13	Mörlialp	1460	–	4.6
14	Rothorn station[b])	1235	±	3.0

[a]) Total disturbance. [b]) Studied in late summer 2007.

Fig. 9. *Topographical map* (adapted from *Google Earth*) *of the main valley of Entlebuch, Switzerland, seen in North–South direction*. Five bug-collection areas are indicated, including Flühli (*1*), Hüttlenen (*2*), Chragen (*3*), Südelgraben (*4*), and Vorderer Hübeli (*5*), of which three (*1*, *2*, and *4*) lie in the main north-wind direction. In contrast, locations *3* (Chragen) and *5* (Vorderer Hübeli) are wind-protected, lying in a side valley and behind a mountain (Schrattenfluh), respectively.

The observation that the wind-exposed true-bug populations in the Entlebuch are significantly disturbed could be related to radionuclides emitted by the Swiss nuclear-power plants Gösgen and Leibstadt, located *ca*. 50 and 80 km, respectively, in northern direction. Thus, radioactive material could be transported in aerosols by means of the Swiss north wind called 'Bise' into the valley, and deposited *via* rainfall and/or fog. Although the level of radioactivity in the more-wind-exposed places might only slightly be higher than in the more protected areas[10]), differential long-time accumulation of tritium (^3H) and other radionuclides in the host plants of true bugs could rationalize the above results. Thereby, artificial low-level radiation must not necessarily induce genetic mutations, but is likely to affect the *morphogenesis* of true-bug larvae. Currently, I do not have any other explanation for this unexpected phenomenon.

In summary, the above studies on different potential reference biotopes suggest that the lower limit of *disturbed* true bugs currently found in Nature lies in the order of 1–3%. From numerous visual inspections of these insects, I further gained the impression that *morphological* malformation is an especially reliable indicator of hazardous influences, and that true bugs respond more sensitively to environmental conditions than generally expected. The lesson to be learned from these experiments is that an apparently intact, beautifully looking biotope, on closer scrutiny, may not be a good choice for a reference biotope at all. Could it be time for a *shift in paradigm* concerning the state of our ecosphere and our romantic notion of Nature?

3.2. *European True-Bug Species.* During my studies on true bugs, mostly performed in Western Europe, some 80 different species were analyzed (*Table 5*). Regarding malformation, I noticed that healthy insects generally showed a very high degree of symmetry, both in shape and pattern, as well as a shiny surface. Each individual bug had its own 'personality', with similar, yet individual, coloration and pattern within its species-specific appearance. Over the years, I observed significant differences in susceptibility towards malformation, depending on family and species. Generally, Pentatomidae, Coreidae, and Pyrrhocoridae[11]) were found to be most sensitive; Miridae, Nabidae, Scutelleridae, Lygaeidae[12]), and Tingidae were less sensitive; and Rhopalidae and Anthocoridae were found to be the least susceptible among the families studied (*Table 5*; see also *Table 7* below). In the case of Alydidae, Stenocephalidae, Berytidae, and Acanthosomatidae, no clear statement could be made due to only limited numbers of individuals found. A more detailed analysis of body-part-specific malformation will be presented in *Sect. 3.4*.

3.3. *Chernobyl-Fallout Areas in Sweden, Ticino (Switzerland), and the Ukraine.* One year after the accident in Chernobyl, I decided to study the true bugs in regions contaminated by fallout from the radioactive cloud. Based on maps showing the distribution of Chernobyl-related radioactivity (see *Figs. 1* and *2*), I decided to travel

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[10]) The presence of low levels of radioactivity, on a microscopic level, is diffult to determine, especially when α-particle- or β-particle-emitting radionuclides are incorporated into organisms, where they can be locally very harmful. For this reason, my data currently rely only on a comparison of true-bug phenotypes. For future investigations, however, it would be desirable to conduct a series of interdisciplinary studies.

[11]) Pyrrhocoridae are represented in Switzerland by *Pyrrhocoris apterus* (fire bug), which, in natural biotopes, is rarely found, in contrast to urban places.

[12]) Except for *Lygaeus saxatilis*, which was found to be fairly sensitive.

Table 5. *Typical True-Bug Species from Western Europe Investigated during This Study*

Family	Species
Acanthosomatidae	*Elasmostethus interstinctus*
Alydidae	*Camptopus lateralis* (rarely found)
Anthocoridae	*Anthocoris nemorum*
Berytidae	*Metatropis rufescens*, *Neides tipularius*
Coreidae	*Coreus marginatus*, *Enoplops scapha*
Lygaeidae	*Lygaeus equestris*, *Melanocoryphus albomaculatus*, *Kleidocerys resedae*, *Scolopostethus affinis*, *Gastrodes grossipes*, *Rhyparchromus vulgaris*
Miridae	*Deraeocoris ruber*, *Deraeocoris trifasciatus*, *Capsus ater*, *Liocoris tripustulatus*, *Orthops kalmi*, *Lygocoris pabulinus*, *Lygus pratensis*, *Lygus wagneri*, *Lygus rugulipennis*, *Stenotus binotatus*, *Calocoris striatellus*, *Calocoris roseomaculatus*, *Adelphocoris lineolatus*, *Adelphocoris seticornis*, *Pantilius tunicatus* (very rare), *Capsodes cingulatus*, *Capsodes gothicus*, *Stenodema laevigatum*, *Stenodema calcaratum*, *Stenodema holsatum*, *Notostira elongata*, *Acetropis carinata*, *Hadrodemus Hadrodemus m-flavum*, *Polymerus microphthalmus*, *Leptopterna dolobrata*, *Alloeonotus fulvipes*, *Cyllecoris histrionicus*, *Orthocephalus brevis*, *Heterotoma planicornis*, *Dryophilocoris flavoquadrimaculatus*
Nabidae	*Nabis mirmicoides*, *Nabis apterus*, *Nabis flavomarginatus*, *Nabis rugosus*
Pentatomidae	*Graphosoma lineatum*, *Carpocoris fuscispinus*, *Carpocoris purpureipennis*, *Dolycoris baccarum*, *Palomena prasina*, *Palomena viridissima*, *Eurydema oleraceum*, *Holcostethus vernalis*, *Picromerus bidens*, *Eurydema dominulus*, *Aelia acuminata*, *Arma custos*, *Pentatoma rufipes*, *Antheminia lunulata*, *Eysacoris fabricii*, *Nettiglossa pusilla*, *Neottiglossa leporina*
Pyrrhocoridae	*Pyrrhocoris apterus*
Reduviidae	rarely found
Rhopalidae	*Corizus hyoscyami*, *Stictopleurus punctatonervosus*, *Rhopalus parumpunctatus*
Scutelleridae	*Eurygaster testudinaria*, *Eurygaster maura*
Stenocephalidae	*Dicranocephlaus albipes* (one individual only)
Tingidae	*Tingis reticulata*, *Acalypta carinata*

first to Gysinge, Österfärnebo, and Gävle, Sweden, then to Melano and Rancate, Ticino, South Switzerland, and finally to the Ukraine, near Chernobyl itself (for geographic details, see *Experimental*).

In these places, I collected relatively small numbers of true bugs (see *Table 1*), because I was mainly working as a painter, without having yet the intention of starting a systematic study. In Sweden, I was very impressed by the grass, which was colored in a dark, rusty red[13]). A veterinarian from Gysinge let me paint a dark-red clover from his garden, which had yellow instead or pink flowers! I painted several heavily deformed specimens of true bugs (Heteroptera) and cicada (Auchenorrhyncha). In *Fig. 10*, a comparison of a healthy (*a*) and disturbed (*b*) damsel bug from Gysinge, Sweden, is

[13]) I only later learned about the 'Red Forest' near the Chernobyl nuclear power plant.

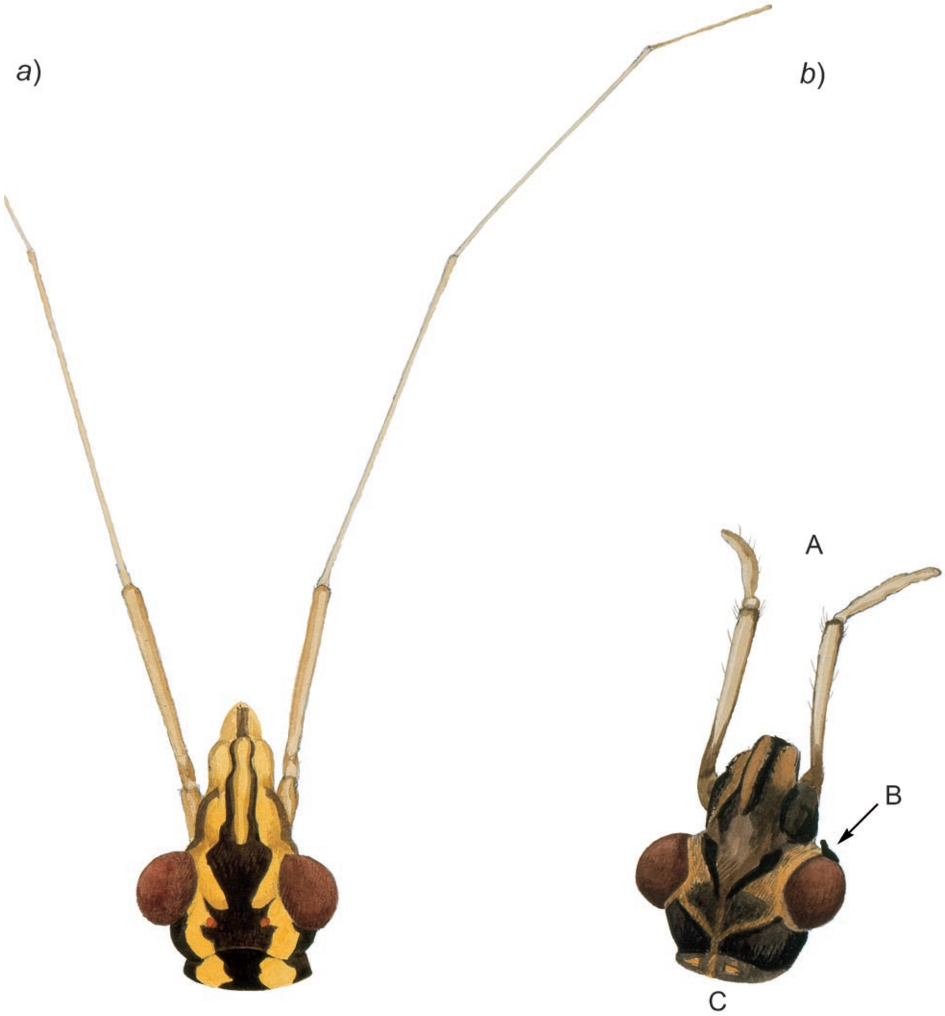

Fig. 10. *Head of a healthy* (*a*) *and a disturbed* (*b*) *damsel bug* (*Nabis rugosus*) *from Gysinge, Sweden* (1987; watercolor). In *a*, only part of the left feeler is shown. The disturbed bug shows two deformed feelers (*A*), a growth on the right eye (*B*), and a head significantly too dark and with an unusual pattern (*C*). © *Cornelia Hesse-Honegger*, Zurich.

presented. The disturbed insect shows malformation of its feelers (*A*), a growth out of one eye (*B*), and a head way too dark and with a highly atypical pattern (*C*).

In Ticino, Switzerland, I collected mostly fire bugs (*Pyrrhocoris apterus*), which, however, later turned out to be not a good choice for a systematic study. Fire bugs live on the ground, feed on dead wood and carrion, and often live in large populations in urban environments. Because they are aggressive and carnivorous, and since they even live in areas sprayed with herbicides and insecticides, no reliable statements can be made in terms of malformation. Most other true bugs, though, behave differently, relying on specific host plants in specific habitats. Therefore, they are usually much rarer than the fire bugs. An example of a malformed, non-fire-bug larva[14]) from Ticino is depicted in *Fig. 11*. As can be seen, the right feeler of this insect is affected, the fourth segment (tip) being too small, too light, and presumably too soft.

Fig. 11. *True-bug larva from Melano, Ticino* (1987). The right feeler is affected, the fourth segment (tip) being too small, too light, and presumably too soft.

In 1990, shortly after the fall of the Iron Curtain, I had the opportunity to travel to the still heavily contaminated area of Chernobyl (*Fig. 12*). There, I visited Pripjat and Seljony Mys (*Fig. 12*,*b*), lying within the 30-km exclusion zone, and Polesskoje and Slavoutich, lying outside of this zone. In Polesskoje, the streets were washed with water twice a day to prevent people from contamination with 'hot' particles. Unfortunately, I did not have the possibility to collect a large number of bugs due to a tight agenda, the high radiation, which prevented stays longer than 10 min to 2 h, and a strict military presence. In total, I collected 55 true bugs, all of which I somehow managed to bring back to Switzerland alive. From these, 12 individuals (*ca*. 22%) were malformed. Two examples of malformed squash bugs (*Coreus marginatus*), both from Polesskoje (1990), are shown in *Fig. 4*,*a*, and *Fig. 13*, respectively. In the former, the left feeler lacks one of the four segments, and in the latter, the cover wings are heavily disturbed.

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14) The exact species remaind unknown due to the larval state, which is difficult to categorize unequivocally.

Fig. 12. *Photos of* a) *the Chernobyl nuclear-power-plant 'sarcophagus' and* b) *the village of Seljony Mys within the 30-km exclusion zone.* Photos by *C. H.-H.* (1990).

3.4. *A Systematic Field Study in Canton Aargau*. The Aargau is a Canton in northern Switzerland, covering an area of *ca*. 1,400 km^2, of which the agricultural area, forests, and population areas account for 45, 37, and 15%, respectively, with *ca*. 580,000 people

Fig. 13. *Dorsal view of* Coreus marginatus (squash bug; head and legs not shown) *from Polesskoje near Chernobyl* (1990). The dark-brown membrane of the left wing and large parts of the right wing (coreum) are disturbed (see also *Fig. 4,a*). © *Cornelia Hesse-Honegger*, Zurich.

living either in the capital, Aarau, or in small-to-medium villages and towns. Four of the five Swiss nuclear-power plants are located in or at the border of the Aargau, including Leibstadt (47° 35′ N, 8° 10′ E; at the Rhine river), Beznau I and Beznau II (47° 33 N, 8° 13′ E; at the Aare river), and Gösgen (47° 24′ N, 7° 55′ E; also at the Aare). Further, in close proximity to Beznau I and II, there is the *Paul Scherrer Institute* (*PSI*; 47° 32′ N, 8° 13′ E), a large nuclear-research facility.

In 1988, I conducted preliminary studies on true bugs in this area to exclude the possibility that nuclear installations have any effect on Nature, as claimed by the authorities. However, I locally discovered heavily disturbed insects, two examples being shown in *Fig. 14*.

For this reason, I decided to conduct a systematic study (1994–1996), including 40 different collection sites (*Table 6* and *Fig. 15*). Some 65 true bugs were collected per each site, giving rise to a total data set of 2,600 individuals. Thereby, 15 geographically predetermined sites (red dots in *Fig. 15*) and 25 arbitrarily determined ones (yellow dots) were chosen, as described in detail in the *Experimental* and in *Fig. 6*.

As can be seen from the data presented in *Table 6*, the range of malformation was 0–15.3 and 3–20% for morphological disturbances (MD) and total disturbances (TD)[15]), respectively, with average values of 6.1 and 10.1%. These average values are clearly above those determined for Swiss 'reference biotopes' (*Table 3*, *Entries 2* and *3*), which are in the range of *ca*. 1.5–3.5% (TD).

In *Fig. 16*, the distribution of total and morphological disturbance are shown as a function of true-bug body parts. The malformation propensity decreased in the sequence wing > abdomen > feeler > thorax > leg > head > scutellum > feet for the total disturbances. A similar picture was obtained for the morphological disturbances, except for wings and abdomen, which were less susceptible than feelers and thorax. Hence, from a morphological point of view, the feelers and thorax showed the highest tendency of malformation, followed by the wings and the abdomen.

In *Table 7*, the corresponding family-specific malformation rates are collected. The 2,600 insects belonged to a total of 15 true-bug families, plus the suborder Auchenorrhyncha (cicada). Pentatomidae (1022), Coreidae (711), Miridae (419), and Nabidae (189) were the most prominent families in terms of number of total individuals. The total disturbance (TD) decreased in the sequence Pentatomidae (13.0%) > Coreidae (10.7%) ≈ Auchenorrhyncha (10.5%) > Miridae (7.4%) > Nabidae (5.8%). For families with few individuals (< 50), no conclusive statement could be made in terms of susceptibility.

In the further discussion, mainly *morphological* disturbances will be considered, because I rate these as more significant. Interestingly, the distribution of morphologically disturbed insects in the Canton Aargau was found to be very heterogeneous. For instance, whereas *no* malformed insects (0%) were found in Othmarsingen (location *9* in *Fig. 15*), some 15.3% of disturbed insects were identified in Rüfenach (location *20*). These, at first glance, apparently inconsistent data prompted me to include direction-dependent annual wind frequencies (wind rose) at the above-mentioned nuclear installations into the analysis. The pertinent meteorological wind data were obtained

[15]) For a discrimination of morphological and other types of malformation, see *Experimental* (*Sect. 2.3*).

a)

b)

Fig. 14. Two soft bugs (Miridae) *collected in 1988 near the nuclear-power plant Gösgen, Switzerland. a*) Partially irregular facets with large lump growing out of the left eye; *b*) differently sized and proportioned wings (the lacking left feeler could have been lost mechanically).

from the Swiss *Meteorologische Zentralanstalt* (for Gösgen and Leibstadt), and from [31] for Beznau and the *PSI*.

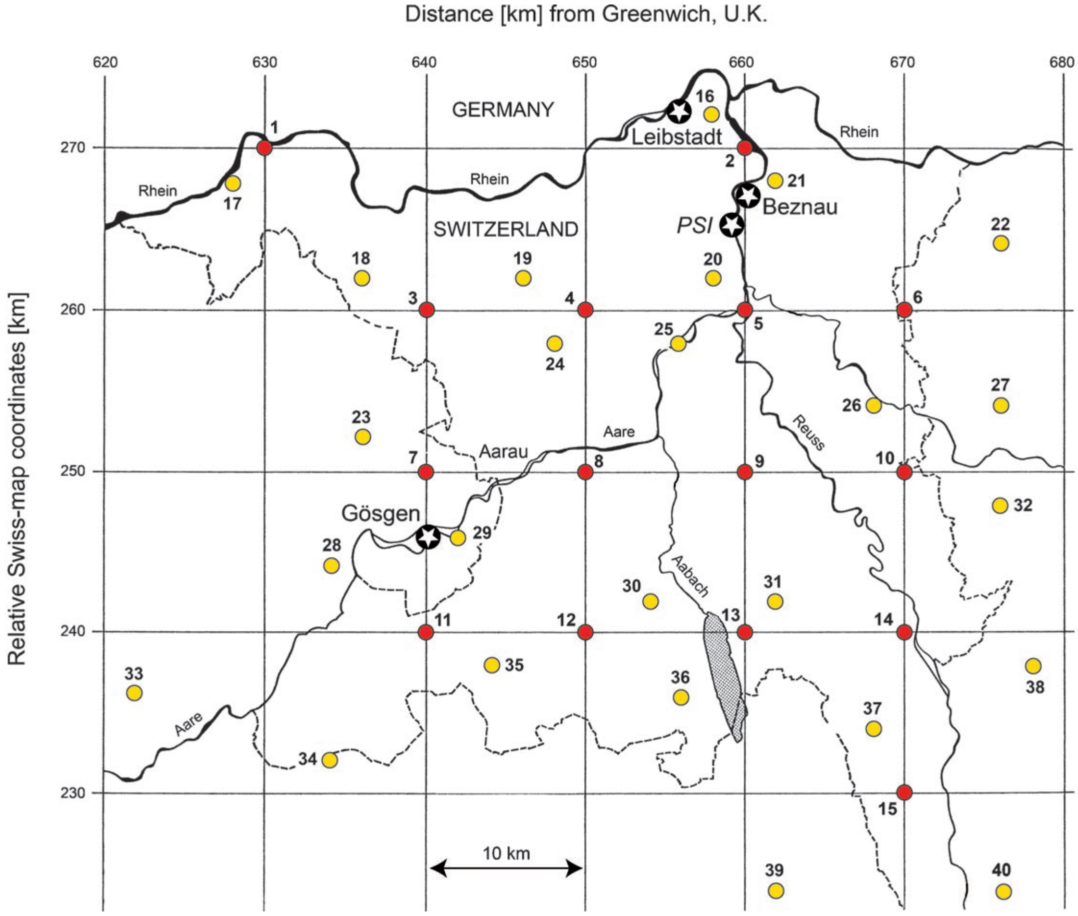

Fig. 15. *Study sites in the Canton Aargau and Surrounding Area*. The 15 red and 25 yellow dots mark field-study collection sites chosen according to different geographical criteria (see *Fig. 6* and *Experimental*).

In *Fig. 17*, the color-coded relative morphological malformations of true bugs at the 40 collections sites (see *Fig. 15*), the positions of the four nuclear installations, and the associated annual wind directions and relative frequencies at these installations, are overlaid. The main two wind directions in Switzerland are NE–SW and W–E. As can be noted, with a few exceptions, the highest malformation (red, violet, and blue dots) was found in NE–SW direction, basically along (or parallel to) the connection line between the nuclear installations. For a more detailed analysis, more collection sites as well as topographical variables would have to be taken into account, which, however, was not possible in the frame of this project[16]). Nevertheless, there was a general tendency of increased true-bug malformation in the vicinity of the nuclear installations,

[16]) I have conducted and paid all research on my own.

Table 6. *Malformation Rates of True Bugs in Canton Aargau and Surrounding Area* (1994–1996). The relative morphological disturbances (MD) and total disturbances (TD) are given in %. Per study site, 65 true bugs each were collected, 2,600 in total. For the geographical choice of the collection sites (*Fig. 15*), see the *Experimental* and *Fig. 6*.

Site	Village/town[a])	MD	TD	Site	Village/town[a])	MD	TD
1	Möhlin	4.6	10.7	*21*	Döttingen	6.1	9.2
2	Kleindöttingen	15.3	18.4	*22*	Bachs	3.0	3.0
3	Homberg	1.5	7.4	*23*	Zeglingen	6.1	6.1
4	Effingen	4.6	9.2	*24*	Zeihen	4.6	7.6
5	Windisch	10.7	16.9	*25*	Brugg	1.5	4.6
6	Steinhof	9.2	16.9	*26*	Killwangen	1.5	6.4
7	Stüsslingen	10.7	13.8	*27*	Regensdorf	4.6	16.9
8	Rohr	15.3	18.4	*28*	Wangen	9.2	15.3
9	Othmarsingen	0	3.0	*29*	Gretzenbach	9.2	16.9
10	Kindhausen	1.5	4.6	*30*	Dürrenäsch	9.2	12.3
11	Safenwil	9.2	9.2	*31*	Büttikon	1.5	3.0
12	Unterkulm	4.6	7.6	*32*	Uitikon	3.0	3.0
13	Sarmenstorf	6.1	18.4	*33*	Kestenholz	9.2	10.7
14	Rottenschwil	3.0	12.3	*34*	Sagen	3.0	3.0
15	Auw	6.1	9.2	*35*	Bottenwil	6.1	7.6
16	Reuenthal	9.2	12.3	*36*	Leimbach	9.2	13.8
17	Rheinfelden	1.5	3.0	*37*	Ättenberg	7.6	16.9
18	Hellikon	1.5	3.0	*38*	Hedingen	4.6	20.0
19	Hornussen	6.1	9.2	*39*	Römerswil	6.1	7.6
20	Rüfenach	15.3	16.9	*40*	Langrüti	4.6	10.7

[a] Name of the village or town closest to the respective collection site.

especially when taking wind into account. These results qualitatively match those of the Entlebuch (see *Sect. 3.1*), where a correlation was found between wind, topography, and malformation.

A possible rationalization of the above results is that the radioactivity emitted in the form of artificial radionuclides from nuclear-power facilities is transported *via* air (wind, fog), and then locally deposited during rainfall. Although the annually emitted doses of radioactivity from nuclear-power plants are relatively low (1–6 μSv, depending on reactor type and power) compared to background radiation (*ca.* 1 mSv), these two types of radioactivities cannot be readily compared with each other. Background radiation is to a large part due to *electromagnetic* radiation (cosmic radiation), whereas man-made, artificial radionuclides emit 'hot' α- and β-particles, which, on a microscopic level, can do much more harm than constant exposure to background radiation. Thus, local accumulation of noxious artificial radionuclides in the biosphere (soil, plants, animals) could, at least partly, be the cause of the observed malformations. Thereby, it is not clear whether these malformations are due to radiation-induced genetic defects or are the consequence of a disturbed morphogenesis during larval development, or both.

3.5. *Nuclear-Reprocessing Plant La Hague.* In 1999, I traveled to France to investigate the true bugs in the vicinity of the nuclear-reprocessing plant La Hague, Normandy, which is operated by *AREVA* (*COGEMA*). There, 50 true bugs each from

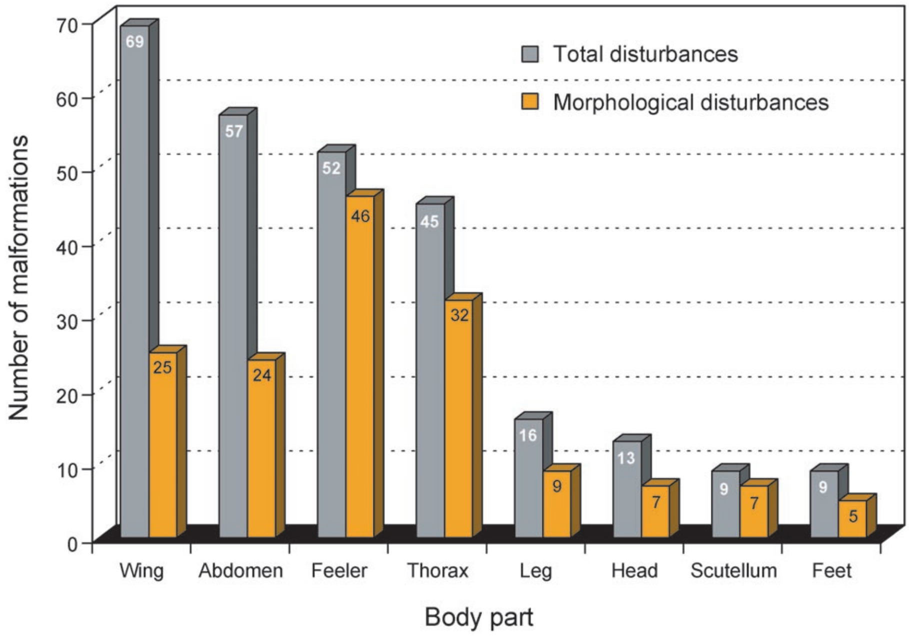

Fig. 16. *Body-part-specific malformation in 2,600 true bugs from Canton Aargau* (1996–1999)

Table 7. *Family-Specific True-Bug Malformation in the Study of Canton Aargau* (1994–1996). A total of 2,600 individuals from 40 locations were analyzed (see *Figs. 15* and *17*).

Entry	Family	True bugs	Number of disturbances	
			TD[a])	MD[b])
1	Pentatomidae	1022	133	78
2	Coreidae	711	76	57
3	Miridae	419	31	16
4	Nabidae	189	11	4
5	Rhopalidae	76	3	1
6	Lygaeidae	47	3	1
7	Anthocoridae	23	2	0
8	Bertydae	11	1	0
9	Scutelleridae	8	0	0
10	Pyrrhocoridae	8	1	1
11	Reduviidae	4	0	0
12	Acanthosomatidae	3	1	1
13	Stenocephalidae	1	0	0
14	Plataspidae	1	0	0
15	Dermaptera[c])	1	0	0
16	Auchenorrhyncha[c])	76	8	1
	Total	**2600**	**270**	**160**

[a]) Total disturbance. [b]) Morphological disturbance. [c]) Dermaptera (earwigs) and Auchenorrhyncha (cicada) were also included in the study, since related to true bugs.

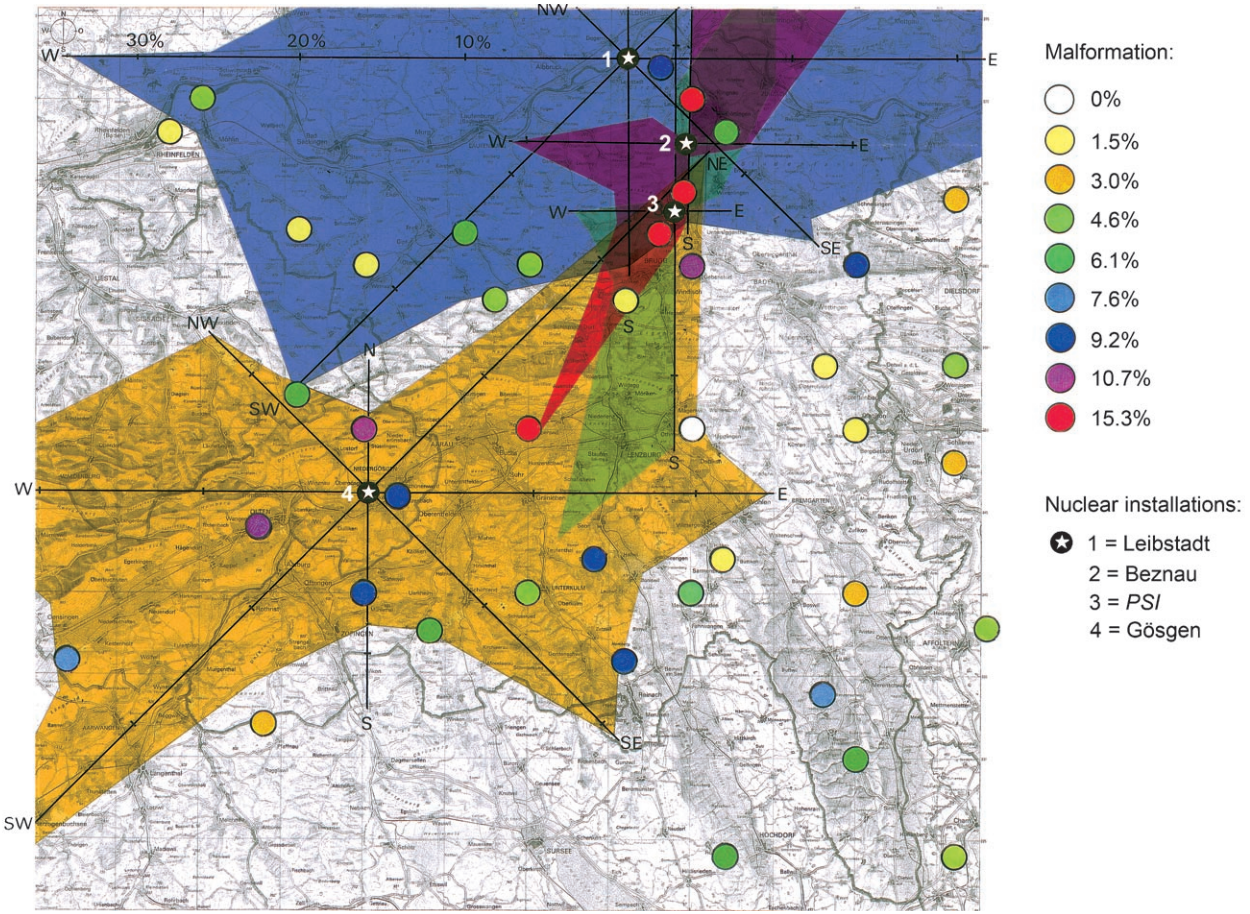

Fig. 17. *Morphological disturbances of true bugs and direction-dependent annual wind frequencies at four nuclear installations* (*1*–*4*) *in Canton Aargau and surrounding area* (1996–1999). A total of 2,600 individual insects were analyzed. The main wind directions are NE–SW and W–E. A higher malformation rate (*red*, *violet*, and *blue* dots) is observed in NE–SW direction *between* the nuclear installations.

13 different locations were investigated (*Fig. 18*), 650 in total. The results, in terms of total (TD) and morphological disturbances (MD), are collected in *Table 8*. The malformation frequency was in the range 6–30% (TD) and 4–22% (MD), with average values of 14.0 and 10.9%, respectively, which again lies considerably above the assumed reference values of *ca.* 1–3%.

The nuclear-reprocessing plant La Hague is located on a plateau *ca.* 180 m above sea level (*Fig. 19,a*), which rapidly descends to the beautiful seashore (*Fig. 19,b*), where most of the collection sites were located. Depending on topography, the high stacks (>100 m) of the plant could only be seen from parts of the above study sites (see qualitative description 'Sight' in *Table 8*). I, therefore, decided to include topographic considerations into data analysis, constructing detailed topographical maps (not shown). In collaboration with Professor *Jean-François Viel*[17]), an exact chi-square (χ^2) test of the data was performed (using the Statxact-3 software) by comparing two proportions (2 × 2 contingency table), *i.e.*, the degrees of malformation of sites from which the stacks of the nuclear-reprocessing plant La Hague were clearly visible ('exposed' sites) with those from which they were not visible ('hidden' sites).

The results were quite unexpected. Depending on topography, the true bugs from the 'exposed' collection sites near the plant showed a much higher percentage of total disturbances (17.8% on average) compared to those collected in 'hidden' places (7.3%), as shown in *Table 9.* In this analysis, we excluded Cap Lévy and La Hogue (*Entries 1* and *2* in *Table 8*), which were too far away for the above local analysis. However, even when including these two additional sites into the analysis, qualitatively similar results were obtained (data not shown).

The above results are remarkable in that they strongly indicate a relationship between true-bug malformation and local topography. The high statistical significance ($p = 0.003$) for differential degrees of malformation for the two classes of collection sites, termed 'hidden' and 'exposed', could be interpreted as follows. The exposed sites are likely to experience more of the strong local downwinds from the higher-situated reprocessing plant, compared to the more-hidden places, *e.g.*, in the back of small hills acting as local barriers or wind shields. Hence, in the more-exposed places, a higher deposition rate and, thus, a higher degree of bioaccumulation of artificial radionuclides can be expected. In *Fig. 20*, some examples of disturbed true bugs (body parts) from La Hague are shown.

3.6. *Studies at the Nuclear-Power Plant Gundremmingen, Germany.* On request of several people living in the sphere of the Gundremmingen nuclear-power plant (*Fig. 21*), I started to investigate the true bugs in this area of Bavaria. A total of 2,900 individuals were analyzed between 2002 and 2004. Here, I will present the detailed results from the 2004 study, including 28 collection sites and a total of 1,400 insects (50 per location), as shown in *Fig. 22*. The collection sites were chosen according to three criteria: *1*) distance from the plant (0.6–35 km); *2*) homogenous radial distribution in all directions; and *3*) visually intact habitat.

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[17]) University of Besançon, Department of Public Health, Biostatistics and Epidemiology Unit, Faculty of Medicine, 2 place Saint Jacques, 25030 Besançon, France.

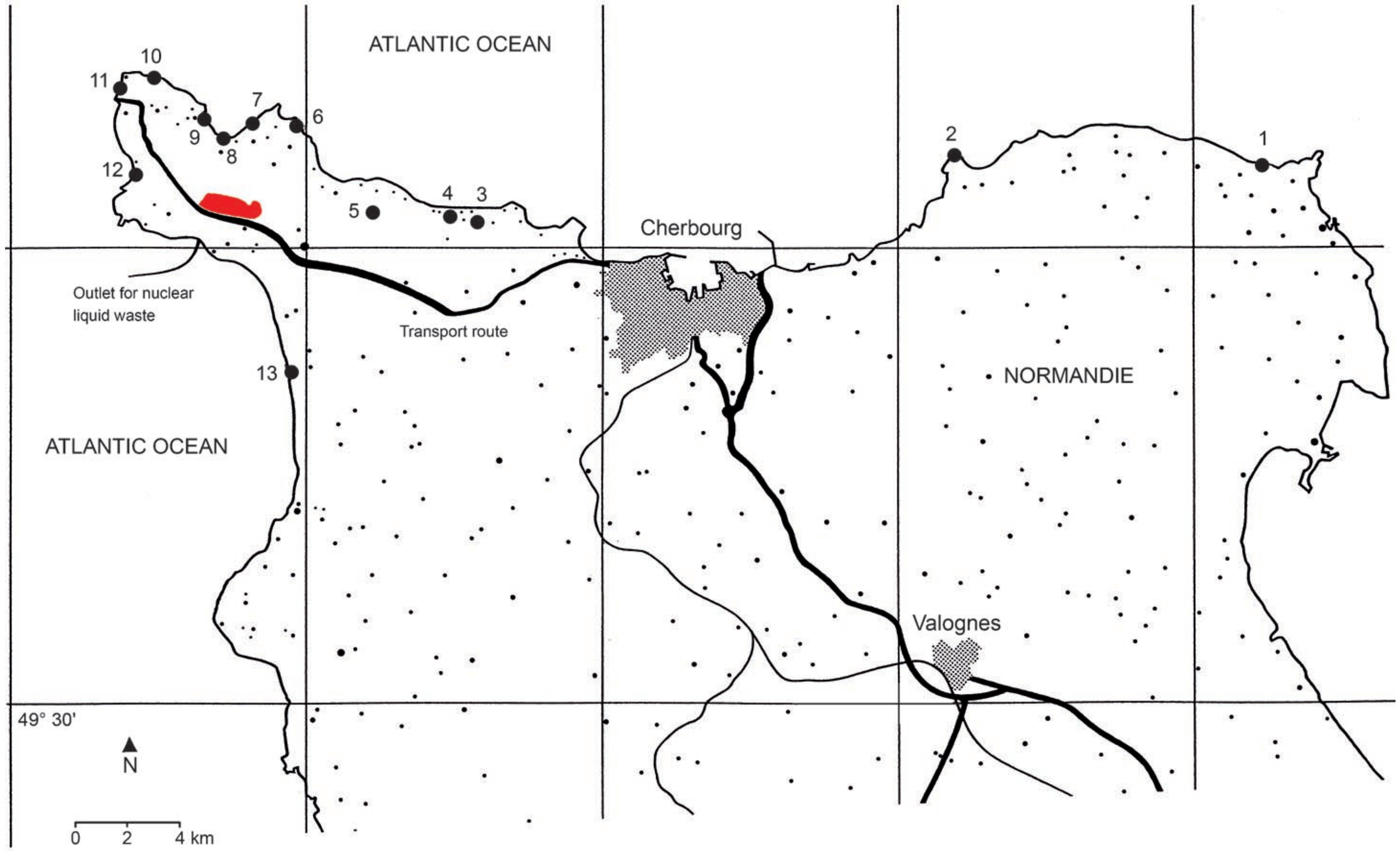

Fig. 18. *Map of the study area in Cape de la Hague, France*. The nuclear-reprocessing plant La Hague is indicated in *red*. For collection sites *1–13*, see *Table 8*.

Fig. 19. *Photos of the nuclear-reprocessing plant La Hague* (*a*) *and of the seashore near La Hague, Normandy* (*b*). The reprocessing plant is *ca.* 3.1 × 0.8 km long and dumps radioactive material into the Atlantic Ocean and the air. The photo in *a* was adapted from *Google Images* (© *Truzguiladh*; CC-BY-SA-2.5), and that in *b* was taken by *C. H.-H.* in 1999.

Table 8. *Collection Sites and Relative Malformation Rates of True Bugs in the Vicinity of the Nuclear-Reprocessing Plant La Hague, France* (1999). See also *Fig. 18*.

Entry	Collection site	Distance [km][a])	Sight[b])	Disturbance [%][c])	
				TD	MD
1	La Hogue	41.50	[d])	10	8
2	Cap Lévy	29.30	[d])	16	14
3	Nacqueville	9.13	–	8	4
4	Dur Ecu	7.18	–	8	8
5	Gréville	3.75	+	26	20
6	Omonville	3.75	+	20	16
	Anse St. Martin:				
7	Les Sablons	3.40	+	10	4
8	Middle of bay	2.65	+	30	22
9	Pointe de Nez	2.65	–	6	6
10	Roche Gelétan	5.18	+	16	10
11	Goury	6.50	+	12	12
12	Ecalgrin	5.50	+	10	10
13	Dunes des Vauville	5.00	+	10	8
	Average			**14.0**	**10.9**

[a]) Horizontal (map) distance from collection site to center of reprocessing plant. [b]) Visual contact possible (+) or impossible (–) to the chimneys of the plant. [c]) TD and MD refer to total and morphological disturbance, resp. [d]) To far away.

Table 9. *Statistical Chi-Square Analysis of the Data Set of True-Bug Malformation as a Function of Local Topography in La Hague, France*. The criteria 'exposed' and 'hidden' refer to collection sites from which the stacks of the La Hague nuclear-reprocessing plant are either visible or not, respectively. The data set included eleven sites (*3–13* in *Fig. 18*), lying in close distance to the plant; 550 true bugs were analyzed.

Type	Average malformation [%]		p[a])	Rating
	'exposed'	'hidden'		
All	17.75	7.30	0.003	highly significant
Feeler	3.75	0	0.01	significant
Thorax	2.0	4.0	0.22	not significant[b])

[a]) Statistical significance. [b]) Too few malformations observed for precise analysis.

The results of the 2004 study of Gundremmingen are collected in *Table 10*. The total and morphological disturbances of the true bugs were in the range 4–26 and 2–22%, respectively, with average values of 13.5 and 10.5%, respectively, way above the expected value for a reference biotope.

From *Fig. 22*, one can see that the aereal representations of the major wind frequencies (NE/SW; light grey) and the relative-malformation frequencies (dark grey) are roughly similar in shape. Interestingly, malformation was *not* highest in the direct vicinity (< 5 km) of the Gundremmingen nuclear-power plant (collection sites *1–5*),

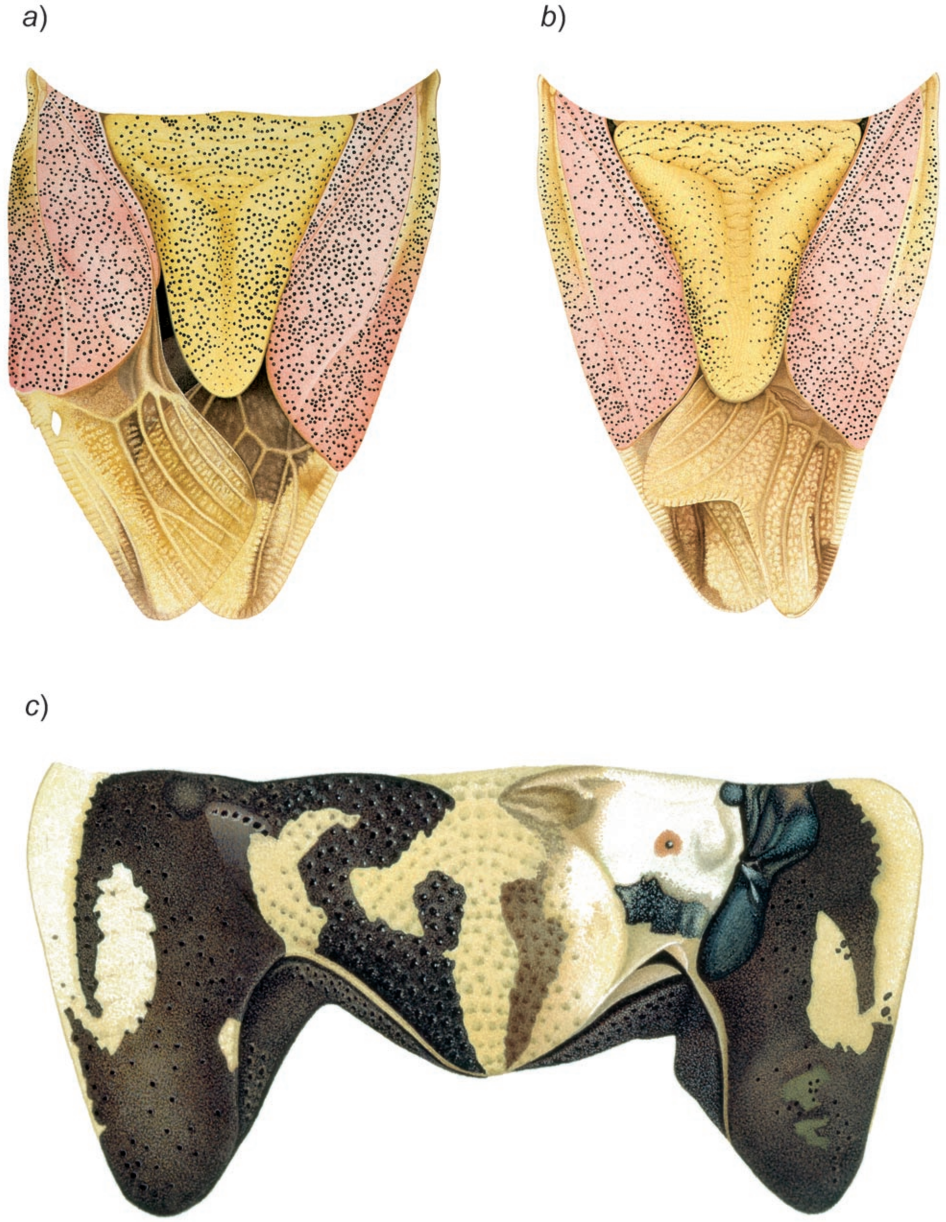

Fig. 20. *Examples of malformed* Carpocoris *species* (*Pentatomida*; body parts only) *collected near the nuclear-reprocessing plant La Hague. a*) Disturbed left wing (shape, coloration), including a hole; *b*) deformed membrane of the right wing; *c*) not yet fully developed wings of a larva, with disturbed texture on the right side.

Fig. 21. *The nuclear-power plant Gundremmingen in Bavaria, Germany.* Photo by *C. H.-H.* (2003).

where the disturbance was in a 'medium'[18]) range (10–14% TD). With a few outliers (*15*, *20*, *27*), most of the medium (*1–6*, *8*, *23*, *26*) and high (*12–14*, *18*, *25*, *28*) malformation frequencies were found at sites lying within the main wind 'channel' (NE/SW), when placing the power plant in the center. Thereby, locations as far away as 36 km were similarly affected as closer-lying sites. Notably, in the southeast (SE) direction, where the winds are least frequent, malformation was less pronounced (sites *10*, *22*, *24*, *27*, and *21*). In *Fig. 23*, selected details of heavily disturbed body parts of true bugs collected near Gundremmingen are illustrated.

To further pin down the above assumed relationship between wind direction and malformation, more data points would, of course, be required to obtain a clearer picture. Nevertheless, qualitatively, the whole situation resembles those of the Entlebuch (*Sect. 3.1*) and the Canton Aargau (*Sect. 3.4*) in Switzerland.

4. Conclusions. – Over the last few years, environmental issues have become more and more important, and a new understanding of the wholeness of Nature seems to be gradually developing. Still, while many people are mostly concerned with daily problems such as climate change, smog, or spoiled water, there is much less consciousness regarding the pollution of the biosphere, especially on a microscopic level. Even more so, the production of atomic energy, often considered a 'clean'

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[18]) The term 'medium' is used here in a relative sense.

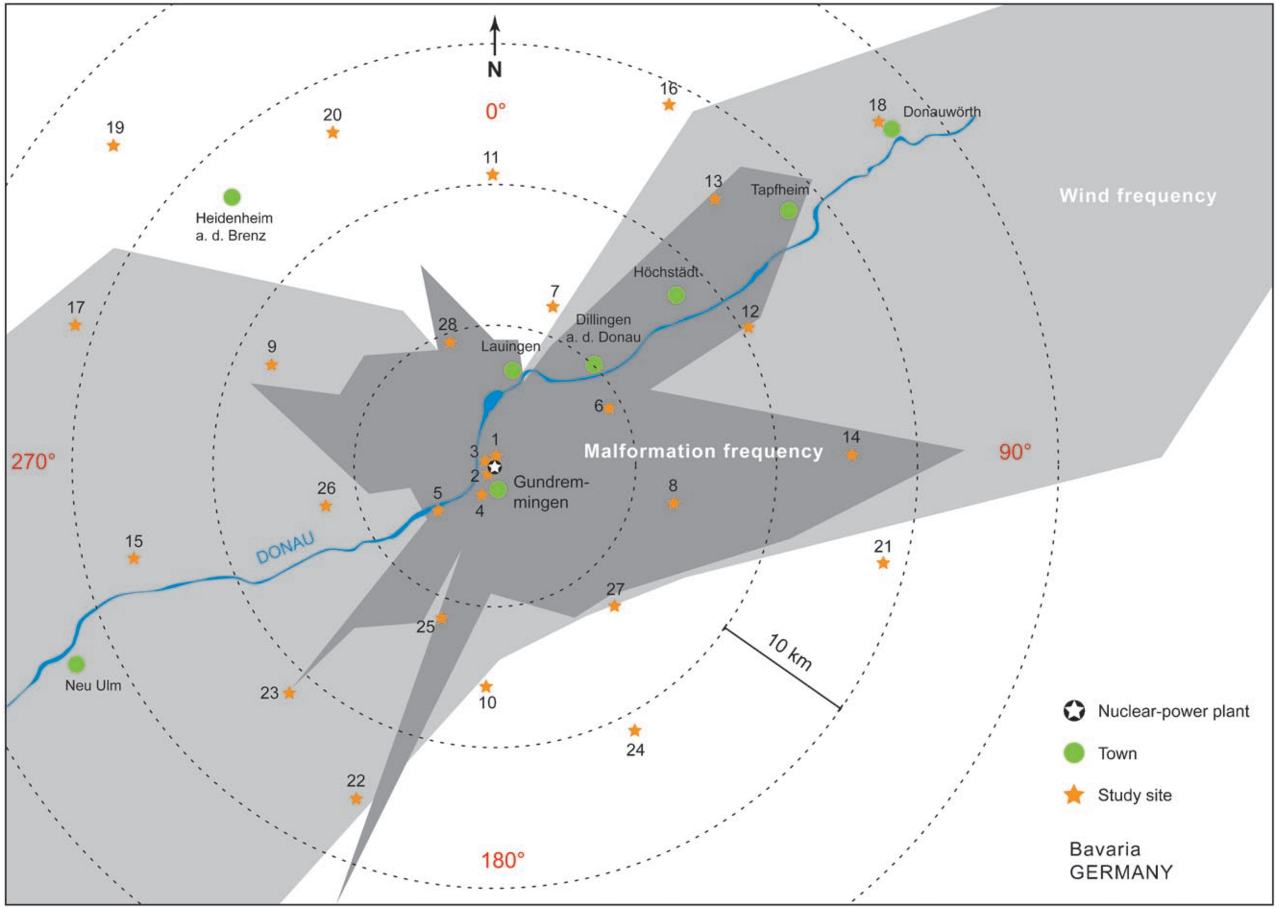

Fig. 22. *Distribution of relative true-bug-malformation frequency* (dark grey) *and major direction-dependent wind frequency* (light grey) *at the Gundremmingen nuclear-power plant*. Winds were measured at an altitude of 113 m above the plant, and averaged for the period March–September 2004 (data from the *Deutsche Wetterdienst* (*DWD*)). The wind- and malformation-distribution areas (arbitrary scale) were derived by converting either direction-dependent wind frequencies or site-dependent number of malformations to relative radial distances, the nuclear-power plant being placed in the center, followed by connecting the corresponding neighboring data points (corners).

Table 10. *Disturbance of True Bugs Collected at 28 Different Locations in the Vicinity of the Nuclear-Power Plant Gundremmingen in 2004.* A total of 1,400 individuals were analyzed. Especially high percentages of malformation are indicated bold.

Entry	Location	Distance [km]	Disturbance [%][a])	
			TD	MD
1	Parkplatz	0.6	10	6
2	Kuhwiese	0.6	12	10
3	Westlich vom AKW	0.9	10	8
4	Westlich von Gundremmingen (Dorf)	0.9	14	10
5	Alter Bahnhof	2.5	12	6
6	Nusser Alm	5.0	14	8
7	Schabringen	9.2	4	4
8	Fultenbach	11.5	12	6
9	Lontal	12.0	**20**	**10**
10	Kammeltal	12.0	8	6
11	Trugenhofen	12.5	12	10
12	Riedschreiner	12.6	16	14
13	Obere Hölzer	15.0	**18**	**18**
14	Osterbuch	17.0	**26**	**22**
15	Elchingen	20.0	4	2
16	Michelsberg	20.0	10	6
17	Kuhberg	20.5	14	14
18	Donauwörth	21.0	**22**	**20**
19	Steinheim	24.0	14	6
20	Kleinkuchen	25.0	16	14
21	Heretsried	25.0	14	14
22	Schiessen	25.5	10	8
23	Hetschwang	26.0	14	14
24	Engertshofen	28.0	8	8
25	Limbach	28.0	**22**	**22**
26	Kieswerk	30.1	10	8
27	Scheppacher	34.9	8	8
28	Pfannental	35.2	**24**	**12**

[a]) TD and MD refer to total and morphological disturbance, respectively

technology[19]), is thought to be safe and efficient. However, as a matter of fact, the more than 210 nuclear-power and nuclear-reprocessing plants worldwide (with over 430 reactors) are constantly polluting the environment; or as *Graeub* says in his standard monograph '*The Petkau Effect*' [23]: '*A nuclear-power plant emits countless of tiny glows in the form of artificial radioactive nuclides.* […] *The multifarious mixture of small doses of highly dangerous radionuclides is randomly scattered throughout the environment, and hence, eludes all control*.' In addition, there is a tremendous load of radioactivity due to military bomb testing, the fallout from Chernobyl, and depleted

[19]) Depending on the quality of uranium ore, the *overall* CO_2 output associated with nuclear-energy production is in the range of *ca.* 0.23–5.9 million tons per 1,000 MW [32], which, in the worst case, is hardly better than producing the same amount of energy by burning charcoal.

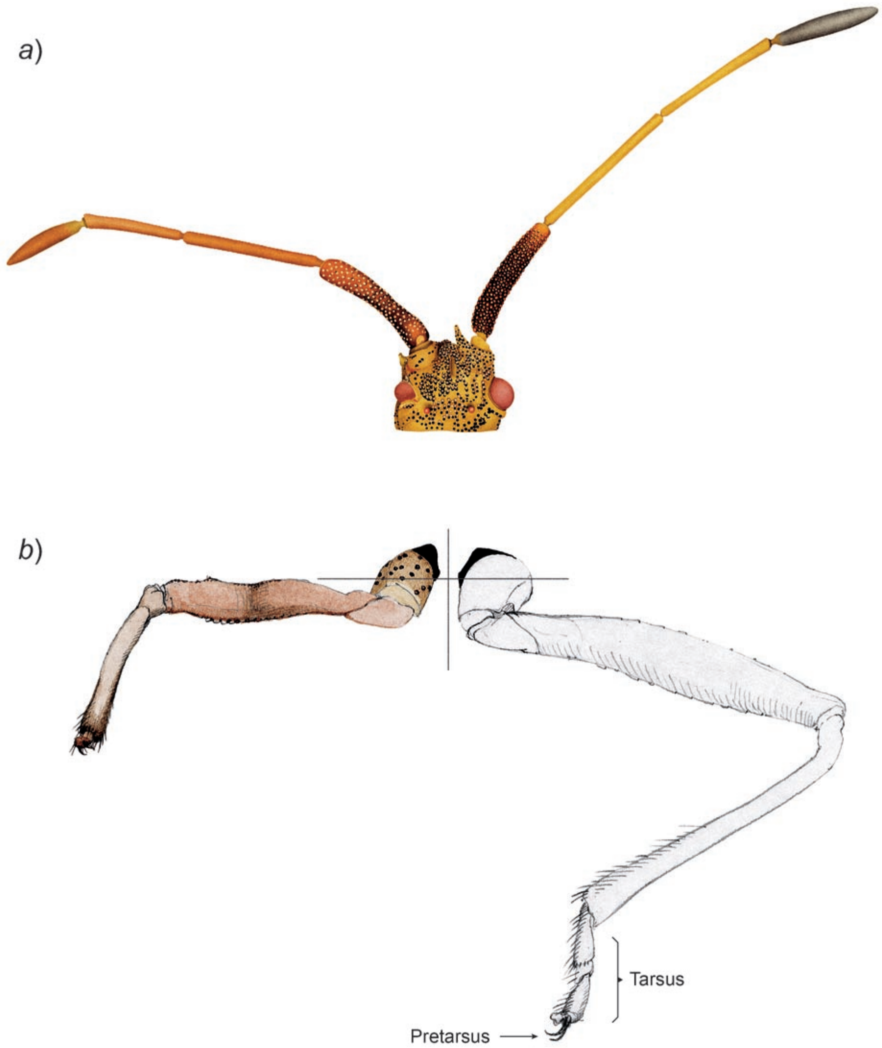

Fig. 23. *Deformed body parts of squash bugs* (*Coreus marginatus*) *collected near the nuclear-power plant Gundremmingen, Bavaria* (2004). *a*) Deformed feeler and head, the left eye being too small; *b*) malformed (*left*) *vs.* normal (*right*) hind legs. The tarsus of the malformed leg has only one segment instead of three; further, the pretarsus ('claws') are too small in the disturbed leg.

uranium ammunition, which makes it difficult to define a proper, unaffected, yet natural, habitat.

My extended work on Heteroptera (true bugs) and related insects seems to confirm the recent findings that *low-dose artificial radioactivity has*, despite much controversy, *a significant impact on the biosphere*. Current methods of extrapolating effects of radiation suffer from several drawbacks. First, there is growing evidence that there is no *linear* relationship between radioactive dose and biological effect [22]. Second, experiments typically conducted on plants and animals with X-rays cannot be compared at all with the effect of anthropogenic, artificial radionuclides ('hot' particles). Finally, experiments performed under laboratory conditions do not mirror what happens in the biosphere, where different environmental effects come into play.

In summary, my field studies show that a significant percentage of European true bugs, living in their specific habitats, are highly disturbed, not only in terms of the actual number of individuals affected, but also regarding the *quality* and *severeness* of malformation. Notably, a non-homogenous distribution of malformation was found, depending on collection site, true-bug family, and affected body part. Especially, major wind directions and topographical situations ('protected' *vs.* 'hidden' places) had to be taken into account to rationalize the data. The geographical distribution of malformed insects as well as the different types of disturbances (phenotype) can only be due to either chemical or radiation effects[20]). However, since malformation was even observed in ecologically 'intact' regions (such as the Entlebuch), yet lying in the sphere of nuclear installations, the second possibility is more convincing. Thereby, it remains unclear whether or not the observed disturbances are a result of morphogenetic or genetic mutations, or both. Only careful breeding experiments with morphologically deformed true bugs, caught in the vicinity of, *e.g.*, nuclear-power plants, can shed further light on this issue.

The present work has two different implications: on one hand, it calls for more systematic studies to address a series of poorly investigated issues, on the other hand, it confronts us with ethical questions regarding Nature and Life in general. From the scientific point of view, it is necessary *1*) to investigate the long-term effects of low-level artificial radiation; *2*) to look at the radionuclide-specific effects on plants and animals; and *3*) to reconsider the current threshold values for radioactive immission. From an ethical and aesthetic standpoint, we should value and preserve both the beauty and highly important function of the large class of insects. Thereby, true bugs, especially *Coreus marginatus* (Coreidae), could serve as sensitive 'bio-indicators' in future studies.

I strongly hope that the growing evidence of severe problems associated with nuclear power will animate the current (and often emotional) political debate on a more scientific level. The latest studies of the German *Kinderkrebsregister Mainz* (*DKK*), confirming a significantly increased rate of childhood leukemia in the vicinity of nuclear-power plants, might only be the tip of an iceberg and should definitely be taken as a serious alarm call.

I would like to thank *Peter Schälchli*, Zürich, for his fabulous photo reproductions of my watercolors.

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20) Note that mechanical effects due to injuries and fights would only explain a small fraction of the observed deformations. In contrast to *Jenny* [27], who found 30% (!) of malformed true bugs (especially fire bugs) in Switzerland, I decided not to include the civilization-adapted, aggressive fire bugs.

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