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Appendix 2

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Appendix 2

Review of Research on Livestock and Crops in Relation to Electric and Magnetic Fields from High Voltage Transmission Lines

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Review of Research on Livestock and Crops in Relation to Electric and Magnetic Fields from High Voltage Transmission Lines

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Contents

Acronyms and Abbreviations

μT	Microtesla
AC	Alternating current
CSF	Cerebrospinal fluid
DC	Direct current
DMI	Dry matter intake
EHC	Environmental Health Criteria
ELF	Extremely low frequency
EMF	Electric and magnetic fields
Hz	Hertz
ICNIRP	International Commission on Non-Ionizing Radiation Protection
IL-1	Interleukin-1
IL-2	Interleukin-2
kV	Kilovolt
kV/m	Kilovolt per metre
m	Metre
mT	Millitesla
PNNL	Pacific Northwest National Laboratory
T4	Thyroxine
WHO	World Health Organization

Executive Summary

A large scientific literature has accumulated since the 1970s investigating potential environmental and health effects of extremely low frequency (ELF) electric and magnetic fields (EMF). Most of the scientific research has focused on potential effects on human health. As part of human health risk assessments, the relevant scientific literature has been repeatedly and systematically reviewed by a number of international and national health, scientific, and government agencies. Perhaps most notably, based on its comprehensive review of the relevant research results, the World Health Organization (WHO) concluded that the available evidence does not confirm the existence of any health consequences from exposure to ELF EMF (WHO, 2007). Known adverse effects, such as nerve and muscle stimulation, which are temporary and reversible, may occur at high exposure levels. Current exposure guidelines applicable in Ireland are stated by the WHO to provide adequate protection for all known effects. Although these guidelines are intended to protect humans against potential adverse effects, there is no evidence to suggest that this protection would not apply to farm animals.

Economic considerations have led to a considerable amount of scientific research, although less systematic in nature, on the potential effects of ELF EMF on livestock and crops. The research studies on livestock tend to focus on species with sizable economic impact, such as cattle, sheep, and swine, and concentrate on outcomes of reproduction, milk production, and growth. ELF EMF research related to plants has been of less interest. Although sporadic associations with various measures from some of the studies on animals and plants were reported, overall, no consistent or convincing pattern of any harmful effects of ELF EMF has emerged in either livestock or crops that would have relevance to farm operations around 400 kilovolt transmission lines in Ireland or even transmission lines operating at higher voltages elsewhere.

This document provides an up-to-date overview and summary of the scientific literature on potential effects of ELF EMF on livestock and crops, including both field observations and experimental studies. Overall, the available scientific evidence summarised in the current report does not provide consistent or convincing evidence that either electric or magnetic fields associated with the Irish electric transmission system may adversely affect the livestock or crops produced on Irish farmlands.

Introduction

Since the late 1970s considerable scientific and public attention has been paid to potential environmental and health effects of extremely low frequency (ELF) electric and magnetic fields (EMF) associated with power generation, transmission, and use. The main focus of scientific research has been on potential human health effects. This resulted in a large body of scientific literature including epidemiologic studies of humans, laboratory studies conducted on various animal species, and studies conducted on cells and tissues.

Less and more sporadic attention was paid to potential ecological effects on wildlife and vegetation. EMF studies related to livestock and crops were primarily motivated by interest in potential effects of economic importance and typically focused on species with significant economic impact, such as cattle, sheep, and swine. The investigated outcomes were also chiefly determined by these economic drivers with attention focusing mainly on reproduction, milk production, and growth of livestock, and the growth and yield of crops.

The objective of this report is to review and summarise research on the effects of power frequency 50-60 Hertz (Hz) fields in the ELF range on livestock and crops to inform agricultural interests whose land might be crossed by existing transmission lines or proposed 400 kilovolt (kV) or lower voltage transmission lines as part of EirGrid's grid development programme.[1] EirGrid reports that a representative magnetic field level directly underneath 400 kV lines is 10.8 microtesla (μT) and a similar representative level of the electric field directly underneath these lines is 3.7 kilovolts per metre (kV/m).[2] It should be kept in mind that the research reviewed below frequently relates to lines operating at much higher voltages (i.e., 500 kV to 1100 kV) or to experimentally produced levels of EMF that are far higher than are characteristic of 400 kV transmission lines in Ireland.

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1 http://www.eirgrid.com/media/GRID25.pdf

2 EMF & You, Information about Electric & Magnetic Fields and the electricity transmission system in Ireland, revised July 2014. http://www.eirgridprojects.com/media/EMF%20%20You%20Booklet%202014.pdf.

The significant amount of health studies conducted on humans and laboratory animals also provides scientific evidence that has relevance for evaluation of potential effects on farm animals. The relevant scientific literature has been repeatedly and systematically reviewed by international and national scientific, health, and government agencies in an effort to assess potential human health risk associated with exposure to ELF EMF. The organizations that completed health risk assessments include the World Health Organization (WHO, 2007), the International Agency for Research on Cancer (IARC, 2002), the National Radiological Protection Board in the United Kingdom (NRPB, 2004), the National Institute of Environmental Health Sciences in the United States (NIEHS, 1999), the European Union's Scientific Committee on Emerging and Newly Identified Health Risks (SCENIHR, 2009, 2013), and the Department of Communications, Marine and Natural Resources in Ireland (DCMNR, 2007). None of these agencies has concluded that ELF EMF is the cause of any adverse health effects, including cancer and non-cancer outcomes. While the expert panels convened by these agencies acknowledged the limited evidence for a statistical association between childhood leukaemia and residential magnetic field exposure in epidemiologic studies, all other evidence from human and laboratory studies was judged to be inadequate (e.g., WHO, 2007). According to the WHO, the "current evidence does not confirm the existence of any health consequences from exposure to low level electromagnetic fields."[3] This scientific conclusion is also relevant to the health and wellbeing of livestock. The available scientific studies do not provide evidence to suggest that exposure to ELF EMF would have any different biological or health effects on farm animals than on humans or laboratory animals. Moreover, the exposure of four-footed livestock to ELF electric fields from transmission lines is considerably lower than humans because of differences in the body shapes and grounding of quadrupeds and bipeds. Based on modeling and some measurements, the average exposures of cows, horses, and swine to the electric field under a transmission line are about 56%, 56%, and 53%, respectively, of that experienced by a person (Kaune and Phillips, 1980; Kaune, 1981; Kaune and Gillis, 1981). For animals with bodies larger than humans, ELF magnetic fields will induce larger electric fields and currents in the body; smaller animals will have lower induced fields and currents. Magnetic field exposures, however, are not known to be perceptible to humans or livestock.

[3] http://www.who.int/peh-emf/about/WhatisEMF/en/index1.html

At high exposure to electric fields (59kV/m according to Reilly, 2011) and magnetic fields (60 millitesla [mT] according to Kavet et al., 2008), which are substantially higher than exposure levels that could be experienced in the general environment or under 400 kV or even under higher voltage transmission lines, there are known biological effects in humans (Kavet et al., 2008). These effects, such as muscle and nerve stimulation, are immediate and reversible, and form the basis of current exposure guidelines. Exposure guidelines, such as the ones set by the International Commission on Non-Ionizing Radiation Protection (ICNIRP), are developed following extensive and comprehensive review of the relevant scientific literature to identify established effects. Exposure limits are then set well below exposure levels where these effects could be observed. The exposure limits set by ICNIRP (1998) are recognised and recommended for implementation by the WHO and are applied in the European Union, and consequently in Ireland. These limits, based on current scientific knowledge, provide sufficient protection of human health for all known adverse effects. The currently available scientific evidence does not suggest that this protection would not apply to livestock, as well.

Research Approaches

Similar to studies in humans, both observational and experimental study designs are employed to study potential biological and health effects in livestock and biological effects in plants. Observational studies have the advantage of following and monitoring animals in their natural environment at exposure levels to which they are typically exposed. Observational studies, however, have substantial limitations. They frequently rely on secondary sources for information gathering, sources not primarily designed for research purposes, resulting in potential misclassification of outcomes due to systematic, if unintentional, under- or over-reporting. Exposure assignments in observational studies are not random and any systematic differences between exposed and unexposed animals may bias and confound the observed pattern in the biological or health outcomes under investigation. Researchers in observational studies are not in control of the actual exposure of the animals, and the animals classified as exposed may receive a lower level of exposure than assumed or only exposed during part of the observation period (e.g., animals grazing on a pasture that is crossed by a transmission line may spend only a fraction of time directly under the line). Mobility is not an issue in observational studies of crops around a transmission line, but unrecognised differences in soil, microclimate, and other factors at varying distances from the line may potentially confound the interpretation of findings with regard to any relationship with EMF if any differences in biological responses are observed between locations.

In an experimental study, investigators typically randomly assign study subjects (animals or plants) to groups with or without exposure; thus, extraneous factors are less likely to influence the results other than chance variability. Exposure levels are also controlled and measured by the investigators in an experimental study, and thus, the actual exposure levels are known, which aids the correct interpretation of the studies. Exposure levels in experimental studies, however, are typically much higher compared with environmental exposure levels; therefore, any potentially observed effect may not be directly relevant for typical exposure scenarios in agricultural operations near 400 kV transmission lines. When potential effects of environmental EMF exposure on livestock, crops or any living organisms are evaluated it is important to consider all available evidence from various research approaches.

Methods

In this report, we provide a review of the available scientific literature relevant to assess potential effects of ELF EMF exposure on livestock and crops. Structured literature searches were conducted according to standard scientific criteria and using a well-defined search strategy to identify literature and publications in this area of interest.

The primary literature search utilised PubMed, a search engine provided by the United States National Library of Medicine and the National Institutes of Health that includes over 15 million up-to-date citations from MEDLINE and other life science journals for biomedical articles dating back to the 1950s (http://www.pubmed.gov). A supplemental literature search was conducted of agriculture, environmental and life sciences, and other scientific databases on the ProQuest DIALOG search service (included CAB Abstracts, Agricola, Agris, BIOSIS, Plant Science, Animal Behavior Abstracts, Zoological Records, PASCAL, and several others) to identify literature and publications that may not be indexed by PubMed. Results were limited to English-language publications for the period from 1960 through 2014.

The titles of more than 1,000 studies and publications were screened from the search results for studies pertaining to effects of EMF on farm animals and crops. From these results, over 200 abstracts were reviewed to determine relevance. Finally, the literature search results were additionally supplemented by a search of Exponent's substantial EMF resource library and by hand-searching the reference lists of the studies and publications selected for inclusion.

Electric and Magnetic Fields

Life in a modern society is unimaginable without electricity. Almost all aspects of life and economic activities, including education, health care, transportation, manufacturing, communications and entertainment, are dependent on the use of electricity. Alternating current (AC) electricity with a frequency of 50 cycles per second (measured in Hz) is the electricity supplied in Ireland by EirGrid and by other utilities in Europe. In other parts of the world, for example, in North America, 60Hz electricity is used. Electricity, whenever it is generated, transmitted, or used, either in residential or commercial settings, is associated with electric and magnetic fields.

Magnetic fields result from the flow of electric currents. Magnetic field strength is expressed in flux density and measured in the units of tesla (T). Levels of magnetic fields common in our environments are generally reported in smaller units of μT, where 1μT is equal to 0.000001T. Electric fields result from differences in voltage or voltage potentials. Electric field strength is expressed in units of volts per metre (V/m) or in kV/m, where 1,000V/m is equal to 1kV/m. Both electric and magnetic fields diminish quickly with distance away from the source. Electric fields are easily blocked by conductive objects, for example, trees, buildings, fences, or even the human body. Unlike electric fields, magnetic fields are not blocked easily by conductive objects.

The 50Hz EMF that is associated with electricity is part of the ELF range (3-300Hz) of the electromagnetic spectrum. The electromagnetic spectrum also includes frequencies of 0Hz (static fields, associated, for example, with direct current [DC] electricity and the earth's geomagnetic field) and higher frequency fields, such as radio waves and microwaves (frequencies in the several hundred of kilohertz to megahertz and gigahertz), visible light, and X-rays and gamma rays with frequencies of billions of Hz. The energy level of electromagnetic fields is dependent on the frequency of the fields. High frequency fields have high energy and are able to ionise atoms, that is, they are able to dislodge electrons from their path around their atomic nucleus, potentially causing damage in living cells (e.g., X-rays). Radio frequencies and microwaves may be able, at very high levels, to heat objects. Fields with lower frequencies at the bottom of the electromagnetic spectrum, such as ELF EMF, have very little energy and have no ionising or tissue heating effects.

Livestock

Cattle

In the scientific literature on EMF and livestock, potential effects of EMF related to health, behaviour, and productivity of cattle have been studied most extensively.

Observational studies

Farm surveys

Some of the early studies were surveys of farms located in close proximity to high voltage transmission lines. These studies typically relied on the farm operators' recall or observations or past records on animal health or productivity. Surveys of farms reported no effect on milk production, reproductive performance, or grazing habits on farms crossed by 765 kV transmission lines—lines with substantially higher voltage than the 400 kV transmission lines proposed by EirGrid—in Indiana, Michigan, and Ohio (Busby et al., 1974; Ware, 1974; Amstutz and Miller, 1980). Studies that compared the rate of adverse effects on cattle living on farms near high-voltage transmission lines before and after the lines were energised (Williams and Beiler, 1979; Martin et al., 1986) reported no association in milk production or reproduction. Several studies in Sweden and the United States compared various animal health measures on farms located close to transmission lines to those on farms farther away from transmission lines. An early survey of dairy farms in Sweden reported some evidence that decreased fertility was associated with extended exposure to 400 kV transmission lines (Algers et al., 1982). A later nationwide survey in Sweden by these same investigators that included 106 dairy cattle herds exposed to a 400 kV transmission line that crossed their pasture reported no differences in reproductive success or milk yield when compared to similar farms where the cattle grazed on land not crossed by a 400 kV transmission line (Hennichs, 1982; Algers and Hennichs, 1985). As Algers and Hennichs (1985) concluded, fertility "was not significantly different between exposed and unexposed groups" (p. 351).

Field studies of grazing animals

Studies with direct observations of animals grazing under high-voltage power lines were conducted to provide more sensitive and reliable evidence on potential adverse health effects associated with exposure to EMF from transmission lines. Although these studies were not experimental in nature, there was a direct assessment of EMF exposure of the animals in these studies and the animals were continuously exposed; thus they provided more direct evidence on a potential association between exposure and any behavioural or biological changes compared with the previously described farm surveys. In a Swedish study, 58 heifers were continuously exposed in pens under a 400 kV transmission line for an average of 120 days to levels of approximately 2 to 6 kV/m and 2µT (Algers and Hultgren, 1986, 1987). The animals were examined throughout the study for reproductive performance (e.g., regularity and intensity of oestrus cycle, progesterone concentrations, and proportion of animals conceiving). Exposure to the high-voltage line was not reported to affect reproductive functions or pregnancy outcomes in the 58 exposed heifers, compared to 58 unexposed heifers. According to the authors, "[n]one of the parameters were found to be influenced by the exposure of the heifers to the 400-kV, 50-Hz transmission line" (Algers and Hultgren, 1987, p. 21).

Scientists at Pacific Northwest Laboratory (PNNL), a U.S. Department of Energy research laboratory in Washington, conducted a series of observations to determine if steers' behaviour is affected by EMF in the immediate vicinity of a 1,100 kV transmission line. The electric field varied between the study years, increasing from about ~ 8kV/m in the earlier years to 13kV/m in the last study year. These electric field levels are substantially higher than those that could be encountered under the 400 kV transmission lines proposed by EirGrid. In each of the five successive years, five steers were released under the power lines and their grazing patterns were observed within strata of various distances from the transmission line during periods with and without the line being energised.

While in the first 3 years of the study, grazing patterns showed no differences between energised and unenergised periods, in the later study years there were some statistical tendencies for the steers to graze farther away from the lines while they were energised compared with unenergised periods. The authors could not determine if the subtle changes were due to audible noise, hair stimulation, shocks, or foraging availability (Rogers et al., 1979; 1980; 1982; Warren et al., 1981).

More recently, Italian scientists compared a number of immunological and haematological parameters between five cows housed in the immediate vicinity of a 380-kV transmission line and exposed to magnetic fields in the range of 2-3μT to five unexposed cows at a different farm (Stelletta et al., 2007). While some differences were observed in concentrations of various leukocyte differentiation antigens among the exposed compared to unexposed cows (e.g., increased CD8+ numbers), these differences appeared to be within or close to the physiological range. Since the study was based on a very small number of animals (five exposed and five unexposed animals on two different farms), and the design was not experimental in nature, any conclusions from the study should be taken as preliminary.

Behavioural studies of orientation to the geomagnetic field

Two recent studies on cattle orientation, published by the same research team, have received considerable media attention (Begall et al., 2008; Burda et al., 2009). Both studies used publicly available satellite images to identify cattle on various pastures in Africa, Asia, Australia, Europe, North America, and South America. In the first study, the researchers reported that cattle tend to orient themselves in the north-south direction, which—according to the authors' hypothesis—is due to a magnetic alignment to the earth's geomagnetic field. Based on direct observations and observations of snow prints of resting animals, similar conclusions were made about observations of a predominately northerly orientation of red deer and roe deer. This argument appeared to be further supported by the observation that body orientation was more aligned with the magnetic North Pole rather than with the geographic North Pole. The potential influence of time of day, position of the sun, wind direction, while discussed, was not accounted for in the analyses.

In the second publication, the authors reported that in the immediate vicinity of presumably AC high-voltage power lines (within 150 metres [m]) this alignment becomes random. The authors suggest that the ELF- EMF from the power lines may explain this observation but no mechanism exists to explain a potential basis for perception of the static geomagnetic field or ELF fields by cows, the former of which is proposed by the authors as a basis for the reported north-south behavioural orientation. These papers were later criticised by other investigators who performed their own analyses (Hert et al., 2011) and were unable to replicate the initial findings. They also pointed out methodological shortcomings, such as the limited quality of the publicly available satellite images, the un-blinded nature of herd and animal selection and evaluation, and that potential alternative explanations to magnetoreception were ignored. As Hert et al. (2011) concluded, these shortcomings "could easily have led to an unsubstantiated positive conclusion about the existence of magnetoreception" (p. 677).

A recently published work designed to replicate the original findings reported mixed results (Slaby et al., 2013). Solitary cows or cows in small groups showed a tendency for north-south alignment, but cows in larger herds did not. The Slaby et al. (2013) study used similar methodology as the original one (Begall et al., 2008), relying on limited quality satellite images, and did not explore potential alternative environmental explanations for alignment (e.g., wind, topography, or the position of the sun).

Experimental studies

Although observational studies on cattle provide valuable input to the evaluation of the potential for adverse health effects, well-controlled experiments, in which the EMF exposure levels and other environmental parameters can be carefully regulated and monitored and various physiological parameters of the animals can be closely observed by the investigators, provide more direct evidence on a potential association between exposure and potential adverse outcomes.

A group of investigators at the McGill University and the Hydro-Québec Research Institute in Québec, Canada designed and conducted a large number of controlled experiments using standardised methods to estimate potential influence of EMF exposure on various physiological parameters of dairy cows. The investigated outcomes included measures of reproductive function (e.g., oestrus cycle and gestational hormone concentrations), quantity and quality of milk production, feed intake, blood concentrations of pineal gland and thyroid hormones, and circadian rhythm. The Québec researchers were the first to test these associations in controlled experiments and their efforts have not yet been replicated or matched by others.

For these series of experiments, the researchers specifically designed and constructed exposure chambers (Nguyen et al., 2005). The exposure chambers could house eight cows at the time in wooden stalls similar to conditions used in dairy farming with confined housing. The exposure chambers were designed to provide uniform exposures similar in magnitude to those the cows would experience standing directly beneath 735 kV AC (60Hz) transmission lines. Electric fields up to 10kV/m and magnetic fields up to 30μT could be generated. These electric and magnetic field exposure levels are substantially higher than those that could typically be encountered under the 400 kV transmission lines proposed by EirGrid. The experimental design (switch-back experimental protocol) typically included groups of eight animals that were exposed for a 28-day period, followed by a second 28-day period with no exposure, and a third 28-day period with exposure turned on again (on-off-on). In some of the experiments a second group of eight cows were exposed in a reverse pattern (off-on-off). Various health, reproductive, and milk production parameters were measured at predetermined intervals and the concentrations at the exposure periods were compared to concentrations at the unexposed periods using various statistical techniques.

Milk production and feed intake

Several of the experiments investigated various metrics of milk production and feed intake as one of the most important outcomes of interest in dairy cows (Burchard et al., 1996; Rodriguez et al., 2002; Burchard et al., 2003; Burchard et al., 2004; Burchard et al., 2007). Dry matter intake (DMI) was investigated in five studies. The three earlier studies reported a slight (about 4-6%) but statistically significant increase in DMI with exposure (Burchard et al., 1996; Rodriguez et al., 2002; Burchard et al., 2003). These variations were well within the reference range and well within the variation between the experiments. The last two experiments that exposed the cows to either electric or magnetic fields did not show a difference in DMI between the exposed and unexposed groups (Burchard et al., 2004; Burchard et al., 2007). Three studies investigated milk yield; two of them reported no statistical change with exposure (Burchard et al., 1996; Rodriguez et al., 2002), while one reported a moderate decrease (~5%) in the exposed group (Burchard et al., 2003). For fat-corrected milk yield, the same three studies showed inconsistent results, one showing an increase, one showing a decrease, and another showing no change with exposure. Other measures that were also investigated in some of the studies, such as fat yield, protein yield, crude protein, and energy consumption showed no consistent changes with exposure.

Reproduction

Reproductive measures, including the length of the estrous cycle and blood progesterone levels, were also investigated as key outcomes in dairy cattle in several studies. The hormone progesterone, which is mostly produced by the ovaries, plays a key role in the estrous cycle and in the maintenance of pregnancy after impregnation. Five studies looked at the potential influence of EMF exposure on blood progesterone concentrations (Burchard et al., 1996; Burchard et al., 1998a; Rodriguez et al., 2003; Burchard et al., 2004; Burchard et al., 2007). While the initial experiment indicated a slight (~9%), but statistically significant increase of progesterone concentrations with exposure in pregnant cows, all of the four follow-up experiments failed to replicate this finding and showed no statistically significant change in the average blood progesterone levels, or at the maximum value, the rate of change and the total cumulative concentration of progesterone hormones. These follow-up experiments that failed to replicate previously published results by this laboratory included both pregnant and non-pregnant cows exposed to either electric or magnetic fields or to both at the same time.

Two studies (Burchard et al., 1998a; Rodriguez et al., 2003), each including 16 non-lactating, non-pregnant, multiparous cows in the experiment, investigated the potential effect of EMF on the length of estrous cycle. They reported slightly longer (~2-3 days) estrous cycles among the exposed cows than the unexposed cows. One of these studies also reported slightly longer (~2 days) luteal phases in exposed cows. These differences were well within the normal range of variation and were not associated with corresponding changes in progesterone concentrations as discussed above.

Hormone concentrations

Melatonin plays a central role in hormone regulation and it has been hypothesised that in humans, similar to light at night, exposure to EMF may suppress melatonin production. Although this hypothesis has not been supported by reviews of a wealth of human and laboratory animal studies (AGNIR, 2006; WHO, 2007), initial preliminary publications describing the hypothesis may have motivated the McGill researchers to examine potential effects of EMF exposure on melatonin concentrations in cattle. The authors further hypothesised that the slight increase in DMI observed among the EMF exposed cows in the early studies may be due to melatonin suppression. This would be, the authors argued, analogous to increased DMI during longer daylight periods in summer when the shorter nights are associated with shorted periods of melatonin increase. One experiment (Rodriguez et al., 2004) reported lower concentrations of melatonin among the exposed cows but only during the day, when the melatonin concentrations are already normally reduced due to daylight. No differences due to EMF exposure were observed, however, in the nighttime concentrations of melatonin in either pregnant or non-pregnant cows (Burchard et al., 1998b; Rodriguez et al., 2004). When electric and magnetic fields were studied separately, no associations between exposure and melatonin concentrations were observed (Burchard et al., 2004; Burchard et al., 2007).

Prolactin, as the main hormone responsible for lactation, was also investigated, but no consistent associations were reported with EMF exposure. Prolactin concentrations also were hypothesised to be influenced by EMF via changing melatonin concentrations. One experiment showed an increase, while another experiment showed a decrease in circulating levels of prolactin among EMF exposed pregnant cows compared to unexposed (Rodriguez et al., 2004; Burchard et al., 2007). Two additional experiments showed no statistically significant change among pregnant and non-pregnant cows (Burchard et al., 2004; Rodriguez et al., 2004). Insulin-like growth factor-1, playing a role in growth and thus of importance to cattle producers, showed no consistent association with exposure electric and magnetic fields separately or in combination (Burchard et al., 2004; Rodriguez et al., 2004; Burchard et al., 2007) . The thyroid hormone, thyroxine (T4), was investigated in one study (Burchard et al., 2006). Overall, average T4 concentrations showed no association with exposure in either pregnant or non-pregnant cows. Among non-pregnant cows, sub-analyses showed somewhat higher T4 concentrations among EMF exposed cows, but only during certain days (day 4 through day 10) of the 28-day exposure periods. The authors concluded that the association was "very moderate" and "does not represent health hazard [*sic*] for dairy cows."

Central Nervous System

The potential effect of EMF on the function of the central nervous system was assessed in studies that examined the cerebrospinal fluid (CSF). CSF surrounds the brain and the spinal cord for variations in fairly stable concentrations of various neurotransmitter metabolites, and macro and trace elements. EMF exposure was not associated with changes in metabolites of neurotransmitters such as dopamine, serotonin, β-endorphin, tryptophan, and norepinephrine. There was, however, a statistically significant increase of quinolinic acid concentrations in the CSF, which according to the authors may indicate the increased permeability of the brain-blood barrier (Burchard et al., 1998c). The authors concluded that this increase was "small" and it is unclear if it has "any functional significance." The concentration of a number of macro and trace elements were investigated in blood plasma and CSF by Burchard et al. (1999). Exposure to EMF was associated with decreased magnesium concentration in plasma. In the CSF, both increases (for calcium and phosphorus) and decreases (for iron and manganese) were observed. None of these findings were ever replicated and, according to the authors, "it is difficult to speculate about the physiological implication of such variations, if any" (p. 363).

Summary of Studies on Cattle

Cattle have been the most extensively investigated species among farm animals in the ELF EMF literature. Farm surveys and field observation of grazing cattle reported no consistent differences in behaviour or productivity on farms intersected by high-voltage transmission lines compared to farms away from transmission lines. A small number of studies with methodological limitations examined cattle orientation in relation to the earth's geomagnetic field and EMF from power lines, but reported no consistent findings. Researchers in Québec conducted a series of well-designed experimental studies to assess the potential effects of exposure to electric fields (up to 10kV/m) and magnetic fields (up to 30μT) separately and in combination on various behavioural, reproductive, and productivity parameters in dairy cattle. While some small differences (a few percent) in some of the investigated parameters were observed (e.g., feed intake, length of oestrus cycle), these differences appeared to be within physiological ranges and showed no consistent pattern. There were no consistent differences in various measures of milk yield (e.g., fat corrected milk yield, fat yield, protein yield), hormone concentrations (e.g., melatonin, prolactin, thyroxine), or neurotransmitter concentrations in the cerebrospinal fluid. As the Québec researchers concluded in one of their most recent papers (Burchard et al., 2007), "[t]he absence of abnormal clinical signs and the absolute magnitude of the significant changes detected during MF [magnetic field] exposure, make it plausible to preclude any major animal health hazard" (p. 471).

Sheep

Observational Studies

The survey of farm animals near transmission lines by Amstutz and Miller (1980) included one sheep farm. Details regarding the sheep were not provided other than that the average weight of 4.5-year-old sheep on the farm was comparable to the state average in Indiana and that some of the sheep received prizes at county and state fairs. Thus, no adverse effects on sheep were reported.

Experimental Studies

To study the potential effects of EMF on the immune system, scientists at the Oregon Health Sciences Center placed 14 8-week-old sheep in a pen under a 500 kV power line for 10 months (McCoy and Hefeneider, 1993). The sheep were exposed to a mean of 5.5kV/m electric fields and 3.77µT magnetic fields. As controls, 15 age-matched sheep were placed in a similar pen away from the transmission line with ambient EMF exposure. In this pilot study, the researchers measured circulating concentrations of an immune regulatory cytokine, interleukin-1 (IL-1), in the sheep blood 2, 5, and 6 months after the start of the exposure, and observed statistically lower IL-1 levels in the exposed group. The investigators also assessed the production of antibodies following vaccination and observed no differences between this immune response of exposed and unexposed groups. Thirteen of the 14 exposed animals also developed fungal dermatitis, and it is unclear if it was related to exposure since the animals were not randomised into the treatment groups. It is also unclear if the observed IL-1 decrease was related to or potentially explained by the skin infection. Two to three months after removal of the sheep from the exposed and unexposed pens, there were no differences in IL-1 concentrations between the two groups.

In a larger follow-up experiment by the same research group, 45 sheep were randomly allocated into 3 groups with 15 animals in each (Hefeneider et al., 2001). The first group was placed in a pen directly under the 500 kV transmission line (exposed to both electric and magnetic fields), the second group was placed under the transmission line with shielding to eliminate or minimise the electric field component resulting in magnetic field exposure only, and the third group, serving as a control group, was placed several hundred metres away from the line in ambient exposure levels. Both IL-1, which is produced by epithelial cells, and interleukin-2 (IL-2) blood concentrations were monitored monthly during the 27-month study period. IL-2, which is secreted by T-cells, was measured as a marker of T cell activity. As the authors concluded, "[w]hen the data were analyzed collectively over time, no significant differences between the groups were found for IL-1 or IL-2 activity" (Hefeneider et al., 2001, p.170). Thus, the initial findings were not replicated in the follow up-study. During the first 12 months of the follow-up study, however, magnetic field levels were lower (~1.1μT) than in the previous study or during the rest of the study (~3.5μT).

Researchers in two separate studies assessed the circulating blood melatonin concentrations and onset of puberty in female lambs (Lee et al., 1993; Lee et al., 1995). In the first study, 20 8-week-old lambs were randomly assigned in equal numbers into either exposed or unexposed groups and followed until age 10 months. The exposed group was housed in a pen under a 500 kV transmission lines (with mean electric field exposure of 6kV/m and with mean magnetic field exposure of 4μT) and the unexposed group was placed in a pen more than 200m away from the power lines (with mean electric fields of <0.01kV/m and magnetic fields <0.03μT). Melatonin concentrations were determined during eight 48-hour periods from blood samples collected every 3 hours. Puberty was determined from blood progesterone levels taken every 2 weeks after age 19-weeks. No differences between the two groups were observed in daytime or night time melatonin concentrations, in the amplitude, phase, or duration of night time melatonin increase, or in the onset of puberty. As the authors concluded, "[t]hese data suggest that chronic exposure of developing female sheep to 60-Hz environmental EMF does not affect the mechanisms underlying the generation of the circadian pattern of melatonin secretion or the mechanisms involved in the onset of reproductive activity" (Lee et al., 1993, p. 857). The second study was a replication of the first study with larger number of animals (15 lambs in each group). As in the first study, no differences were observed in melatonin concentrations or onset of puberty between the exposed and unexposed animals. The replication study, as the authors put it, "produced essentially the same results" as the previous one.

The potential effect of EMF on cortisol secretion, which can be elevated in ‘stressful’ situations, and growth was investigated in 20 ewe lambs randomly assigned into exposed and unexposed groups in equal numbers between the age of 2 and 10 months (Thompson et al., 1995). Exposed animals were housed under a 500 kV transmission line while unexposed animals were housed more than 200 metres away from the line. Cortisol concentrations were determined from blood samples collected during eight 48-hour periods. No differences were noted in cortisol concentrations and weight gain during the study period between the exposed and unexposed lambs.

In an experimental study to examine whether exposure to EMF may contribute to more frequent or more rapid development of tumours, 88 sheep previously inoculated with bovine leukaemia virus were randomly assigned into two groups in equal numbers (Miller and Lamont, 1996). One group was housed under a 345 kV transmission line, while the other group was housed 500 feet from the line. During the first 5.5 years, no differences were noted in the number of animals removed due to diseases (22 in the exposed and 28 in the unexposed group) or in the number of animals with lymphosarcoma or lymphatic leukaemia (14 in the exposed and 17 in the unexposed group).

Summary of Studies in Sheep

Several experimental studies investigated potential effects of EMF on the immune system, hormone concentrations (melatonin, cortisol), and onset of puberty and tumor development in sheep. No consistent differences between sheep exposed to EMF from transmission lines and unexposed control sheep were reported in these studies.

Swine

A survey of 11 farms near a 765 kV transmission line reported no influence of the line on the health, performance and behaviour of livestock (Amstutz and Miller, 1980). Although two of these farms had pigs, no separate analyses for swine were provided. No adverse effects on pigs were mentioned in the report.

Hjeresen et al. (1982) monitored the behavioural responses of 32 miniature swine exposed to 30kV/m electric fields during a 21-hour test period. The animals tended to spend more time in shielded areas, where the exposure was <1kV/m, than in unshielded areas exposed to 30kV/m electric fields. This effect was primarily observed in swine that were previously exposed to 30kV/m electric fields and not in previously unexposed animals. The effect was also restricted to the dark period and to non-pregnant swine. The electric-field exposure levels in the study were far higher than exposures that could be observed in the environment under a 400 kV transmission line.

Hanford miniature swine was used to evaluate the potential reproductive, developmental, and teratologic effects of chronic, long-term (20 hours per day, 7 days per week) exposure to 30kV/m electric fields in a multi-generation study (Phillips, 1980; Sikov et al., 1987). Reproductive (e.g., implants per litter, prenatal deaths) and developmental (e.g., weight and size of foetus) measures tended to show no consistent differences between exposed and unexposed animals across the three generations. There appeared to be more malformations in the exposed group compared to the unexposed group, but only in some of the generations. As there was an outbreak of *Campylobacter spp.* infection among the study animals prior to rebreeding, the authors also discuss the possible role of this infection in the development of the observed malformations. Since the incidence of malformations also varied between generations, the authors concluded that it was "impossible to conclude unequivocally" whether the observed differences in the frequency of malformations were due to high electric field exposure.

To assess potential effects of EMF on production and reproductive parameters in swine, scientists in Iowa randomly assigned 60 cross-bred pigs in equal numbers to an exposed group (housed under a 345 kV transmission line) and to an unexposed group (housed about 809 m away from the transmission line) (Mahmoud and Zimmerman, 1983, 1984). Electric-field levels in the exposed groups were about 4kV/m, no magnetic-field values were provided. No statistically significant differences were noted between the groups in behaviour during the experiment or in backfat thickness and other carcass quality measures after slaughter of the animals. The offspring of the exposed and unexposed animals were also examined. No statistically significant differences were observed between the exposed and unexposed groups in weight gain, feed intake, feed-to-gain ratio, or carcass yield, grade, and backfat thickness in the offspring. In a follow-up experiment, reproductive parameters were further assessed (Mahmoud and Zimmerman, 1984). The authors concluded that "the results indicate no effects" due to exposure on the rate of pregnancy, litter size, and the number of pigs born alive.

Summary of Studies on Swine

One study showed avoidance of very high electric fields (30kV/m) in miniature swine. The electric field exposure levels in the study were far higher than could be observed in the environment under a 400 kV transmission line. A study of production and reproductive parameters in swine reported no effects of EMF exposure from a 345 kV transmission line. A multi-generation study of miniature swine and electric fields exposure reported inconsistent findings when developmental effects were evaluated. These observations could not be replicated in other species.

Horses

A survey of 11 farms near a 765 kV transmission line reported no influence of the line on the health, performance, and behaviour of livestock (Amstutz and Miller, 1980). Although one of the included farms also had horses, no separate analyses for horses were provided. No additional studies examining potential effects of EMF from transmission lines on horses were identified in the literature. Several studies identified in the literature search used horses to study and demonstrate the beneficial effects of electromagnetic stimulation on bone healing (Collier et al., 1985; Cane et al., 1991; Cane et al., 1993; Zucchini et al., 2002), which is also a recognised therapeutic application in humans.

Summary of Studies in Horses

No scientific studies of potential adverse EMF effects on horses were identified in the literature.

Poultry

Two experiments investigated growth and fertility of poultry in a laboratory environment exposed to 60Hz electric and magnetic fields (Krueger et al., 1972; Krueger et al., 1975). The first study examined the growth experience of male chicks during the first 4 weeks of their life when exposed to extremely low frequency electric or magnetic fields (60Hz and 45Hz) and compared them to the growth experience of unexposed chicks during the same interval (Krueger et al., 1972). Exposure to 60Hz electric (~3.4kV/m) or magnetic fields (~120µT) was not associated with changes in livability, activity, behaviour, or feed utilization. According to results presented by the authors, chicks exposed to 60Hz electric fields also did not statistically differ in weight at any of the four time periods investigated (day 1, 9, 21, 28) from unexposed controls. Chicks exposed to 60Hz magnetic fields had statistically lower weight (a decrease of approximately 8.6%) compared to the unexposed controls at day 21, but not on other days. Overall, no consistent pattern was observed with exposure 60Hz electric and magnetic fields. The 60Hz magnetic field exposure in the study was significantly higher than exposure levels that could be expected under a 400 kV transmission line.

The second experiment investigated various variables of layer hen fertility with exposure to 60Hz electric (~1.6kV/m) and magnetic fields (140µT) during three consecutive 4-week exposure periods (Krueger et al., 1975). Exposure to 60Hz electric fields resulted in statistically significant reduction in egg production during the first two 4-week periods, but egg production returned to levels comparable to controls during the last 4-week periods. In contrast, exposure to 60Hz magnetic fields was not related to egg production during the first two 4-week periods, but was associated with a statistically significant decrease in the last periods. No consistent associations were reported between exposure and fertility, hatchability, or macroscopic abnormalities in hatched chicks. The 60Hz magnetic-field exposure in the study (140µT) was significantly higher than exposure levels that could be expected under a 400 kV transmission line.

Motivated by prior evidence suggesting that the earth's geomagnetic field may play a role in orientation, navigation, and migration of certain avian species, an experimental study using two roosters and two hens (all 10 weeks of age) was carried out to examine the potential for perception of strong 60Hz (1.7mT) or static (4mT) magnetic fields by domesticated chickens (Clarke and Justesen, 1979). Variability in feeding behaviour was assessed during repeated short (90 second) periods of exposure and compared to variability during periods of sham exposure. The investigators chose to examine variability in behaviour, as opposed to frequency of feeding responses, because prior observations showed both suppression and acceleration of feeding responses during the exposure periods. The authors reported increased variability in feeding behaviour while exposed to either ELF or static fields compared to unexposed periods and concluded that chicken may sense the presence of magnetic fields. The authors, however, were unable to rule out the possibility that the observed changes were in response to "artifactual sensory cueing borne of vibration or heating" from the exposure system.

A study by Durfee et al. (1975) investigated potential effects of 60 Hz magnetic (up to 3mT) and electric fields (up to 3.6kV/m) on embryonic and post-hatching growth and development in domestic chickens. The authors reported no consistent or significant effects on hatchability of fertile eggs, embryonic mortality, or growth, development, and memory consolidation of chicks after hatching, up to 10 weeks of age. Smith (1975) examined, in three experiments of 10 chickens each, the potential effects of 45Hz magnetic field (800μT) on social behaviour (pecking order) of domestic chickens. The author reported no consistent pattern based on the results of the three experiments, and concluded that "no clear statement could be made" on any potential effect.

Numerous studies have used chicken eggs as test organisms in laboratory studies, but no consistent pattern of effects of exposure to EMF has been reported across a range of field intensities and such studies, unless very well controlled, are subject to artifacts. While reviewing relevant research studies to evaluate potential reproductive and developmental effects of exposure to EMF, the WHO's Environmental Health Criteria (EHC) has also reviewed experimental studies conducted in non-mammalian species, including chick embryos (WHO, 2007). The WHO EHC observed that while some of the studies may have raised the possibility of a potential effect, "findings of non-mammalian experimental models generally carry less weight in the overall evaluation of developmental toxicity than those of corresponding mammalian studies." Overall, the WHO concluded that the evidence from animal studies for any reproductive or developmental effect attributed to EMF was inadequate.

Summary of Studies on Poultry

A small number of studies investigated potential effects of EMF on growth, development and fertility in poultry. In most of the studies, magnetic field exposure levels were far higher than that could be observed in the environment under a 400 kV transmission line. Overall, these studies showed no consistent effects.

Crops

Field Studies

There is a long history of agricultural experimentation to assess the beneficial effects of electricity on crop yields, yet the studies were typically poorly controlled (Lee, 1996). A review by biologists at the U.S. Department of Energy concluded that the "[o]verall results of the studies indicated that the transmission lines had no noticeable influence on the growth or productivity of the crops" (Lee, 1996, p. 4-55). Better-controlled studies began in the 1970s in which scientists conducted field studies of a variety of crops grown near 500 kV and 765 kV transmission lines. Unfortunately, most of these studies were not published in scientific journals and are therefore unavailable for independent review and evaluation. In general, the later field studies described below were better controlled than these earlier studies.

Studies conducted by PNNL in Washington State investigated plant responses to ultrahigh voltage test lines charged to 1100 kV. Such test lines are a source of electric fields because of the voltage applied, but since they carry virtually no current, they are not a source of magnetic fields.

Rogers et al. (1979) reported on the first partial year of data collected in 1977 on peas and barley in treatment and control conditions after the 1100 kV test line was energised. No differences in seed pod or seed production of peas were noted but pod and seed biomass of exposed pea plants was significantly increased. Statistically significant differences between treatment and control plots for barley were reported; the barley stem length and seed head lengths were slightly greater and the leaf lengths slightly shorter in the treatment plot than in the control plot.

Rogers et al. (1980) summarised the 3 years of data (1977-1979) collected on peas and barley grown in electric fields between 7-11kV/m (field levels far higher than those that could be encountered under 400 kV lines) and control conditions. Lee and Clark (1991) also reported on data collected in 1977-1980. There were no consistent differences reported for barley or peas, except that the growth of barley leaves was slightly lower in all 3 years. The authors suggested that this may be related to the electric field, particularly because the pots containing the barley were elevated above the ground to prevent damage by rodents, which further increased the electric field, but no damage to leaf parts was observed. Similar assessments of the growth of velvet and bent grasses (leaf length, seed head length, stem lengths, biomass) by Rogers et al. (1980) in zones about the line with maximum electric field strengths of about 7.0, 4.0, and 1.0kV/m were made during a 3-year period. Overall, Rogers et al. (1980) stated “no substantial effects were noted” (p. 8.7) and there was “no evidence that the 1200-kV line affected the leaf tips in any way” (p. 8.3), but a reduced growth response was noted in the last year when the electric field increased by 3kV/m in the highest exposure zone (i.e., to 10kV/m).

Based on suggestive findings regarding peas in earlier years, PNNL continued research on peas in 1980 (Warren et al., 1981). In that year, the exposures in plots near the 1100 kV test line were higher, averaging 12kV/m. Pea seed and pod production and weights did not differ between control and exposed sites, but stems and leaves were significantly smaller at the exposed site. Pasture grass studies reported significant differences between velvet and bent grass growth and velvet grass stem length in some zones that was not clearly related to the intensity of the electric field, but no differences in seed head lengths. For velvet grass, the investigators noted that growth of seed heads was greater in the exposure zone than the control zone in the year before the test line was energised, indicating that the interpretation of differences in crop growth after energization needs to consider factors unrelated to electric field exposure. An additional crop, Ladino clover, was studied in this year and no differences were found in seed weights of the most exposed clover and the clover grown in control sites.

To address the possibility that the differences between exposure zones around the 1100 kV test line reflected subtle differences in their microclimate, the design of the crop studies was changed in 1981 so that crop plants at each field location were compared to plants at the same location, but which were totally shielded from the electric field by Faraday cages (Rogers et al., 1982). No differences between shielded and unshielded peas in any parameter within distance zones from the line were observed despite a four-fold increase in the number of samples collected over previous year, which increased the statistical power to detect an effect. Significant differences between the number of pods and seeds and weight of seeds between shielded pea plants in treatment and control areas were found. Since these differences cannot be due to differences in exposure to the electric field (the electric field is zero in both these shielded groups), the investigators suggested that the differences arose because of differences in the microclimate between the line zone and control zone locations.

In 1981, more barley straw was produced in exposed zones than the control zone as in previous years, which also was suspected to be due to differences in microclimates (Rogers et al., 1982). Barley seed head and straw production was greater in the exposed zone than in the control zone, a difference that was eliminated by shielding plants. The shielding itself, however, was suggested to have an effect, as the seed head and straw production of shielded barley plants in the control zone was greater than in unshielded plants. With respect to the pasture grass growth studies, differences in exposure to electric fields at 12kV/m, 2kV/m, and 1kV/m did not affect seed head length in 1981 or in any previous year. No consistent differences in leaf length or stem length in either grass species across exposure zones were apparent, but the stem lengths of bent grass shortened with distance from the line and associated lower electric fields. Shielded velvet grass in all three exposure zones had longer leaf lengths than unshielded grass, whereas a greater stem length of shielded bent grass over unshielded bent grass was observed.

The results of plant studies in 1982 prompted investigators to test the hypothesis that the shielding itself enhanced growth conditions and accounted for the differences described above in the 1982 studies. The studies conducted in 1983 were designed to test the hypothesis. Plots of velvet and bent grass were planted at nine locations at varying distances from the test line at which the measured electric field varied from 12kV/m closest to the line to 0.4kV/m furthest from the line. At each location the plots of plants were surrounded by grounded metal screens, identical simulated screens made of plastic, or no screens. The growth of stems or leaves of the grasses in the electrically shielded and simulated shielded plots were quite similar but the growth of grasses in both shielded plots was significantly greater than the growth observed in the unshielded plots. The authors concluded that the electric field did not influence the growth rate of the grasses but the shielding *per se* did enhance growth. No specific factor was identified that increased growth in the shielded plots, the authors suggested that the shielding created a micro-habitat that was more favorable to growth.

A field study from the University of Notre Dame in Indiana (Greene, 1983) reported on the growth of yellow onions for 5, 10, and 15 days in flats placed on the ground or on top of a 1 m-high wooden post at 6.1, 12.2, and 23m from the centerline of an experimental 765 kV test line. Electric fields of 15.5kV/m, 12.5kV/m, and 7.8kV/m, respectively, were measured at these locations. These electric field levels are far higher than those that could be encountered under 400 kV lines. Other flats of onions placed at 6.1 and 12.2m from the line were covered with a grounded Faraday cage that reduced the electric field to 0kV/m. Two flats of onions were placed 274m from the line where the electric field was measured to be <0.13kV/m. At the end of each of the three sampling periods, the root tips from three to four bulbs were removed, stained, and examined under a microscope to assess the percentage of dividing cells (mitotic index). The data were collected in three separate experiments. Although the authors found statistically significant differences between the mitotic indices of the nine exposure conditions, they did not report that the differences were related to the strength of the electric field. The authors also summarised the results of another investigator, K.S. Rai, who exposed onions to this same transmission line but "found no evidence of altered mitotic rate, change in present of chromosomal abnormalities, or percent of heteropycnotic nuclei" (p. 360).

Investigators from the University of Arkansas sampled 7 cotton fields, 12 rice fields, and 15 soybean fields crossed by a 500 kV transmission line (Parsch and Norman, 1986). The average dried weight of 60 cotton samples and 75-76 soybean and rice samples collected under the transmission line were compared to the average weights of the same number of samples collected 150 feet from the line. No significant differences were reported between the yields of rice and soybeans in the zones under and away from the line, but the yield of cotton was 15% lower in the zone under the line. The investigators indicated that the study could not determine if the EMF from the line or ineffective aerial spraying of chemicals might have explained the difference in cotton yields. Other factors to be considered included soil compaction by construction equipment when the line was installed, differences in microclimate as suggested in the (Warren et al., 1981) study, or sampling error. The latter is a factor because far fewer cotton fields and fewer samples in each cotton field were tested than for rice and soybeans. The methods and results were only briefly summarized in this publication.

A team of investigators from several Italian institutions published preliminary findings from a series of studies on several generations of wheat plants grown with exposure to electric fields of 5kV/m and 20kV/m near a 1000 kV experimental test line (Conti et al., 1989). No differences in indicators of plant development (stem length, number of nodes, number of stems, spike length, spikelets to spike ratio, or dry weight at four developmental stages), chlorophyll or germination capacity (seedling growth; enzymatic activity, and embryo protein, polyamine and RNA concentrations) were reported. The data and methods reported were not sufficient to permit a detailed evaluation.

The most recent field study was published by Austrian environmental and agricultural scientists in 2003 (Soja et al., 2003). Winter wheat and corn was planted at distances of 2, 8, 14, and 40m from a 380 kV transmission line at which average electric field strengths of 3.9, 2.2, 1.0, and 0.2kV/m and average magnetic field strengths of 4.5, 3.7, 2.6, and 0.8μT, respectively, were measured. The growth and yield of these crops between 1993 and 1997 in these four areas was recorded. Two layers of soil were removed in the test area and mixed to achieve a homogeneous soil matrix, which was confirmed by nutrient and elemental analysis, and the plants were planted within circular concrete rings.

No statistically significant differences between the grain or straw yields of winter wheat grown in the highest and lowest exposure zones were reported at the $p = 0.05$ criterion level. No trend was reported for parameters of corn yield or soil microbial biomass to vary with distance (and hence EMF strengths) from the line. *Post hoc* analyses of wheat productivity based on segregating years with dry and wet weather suggested "a minor trend towards lower grain yields nearer to the transmission line" in years of drought stress, but an opposite trend was apparent in the yield of corn in drought years with distance from the line. Given that the reported variation of yields was reported to be 11% with zones at the same distance from the transmission line and yield differences of 57% between drought and humid years, the authors cautiously concluded that "the results of 5 years of field experiments were combined, [and] no unequivocal relation between the high voltage transmission line and crop yield was demonstrated" (p. 100).

Experimental Studies

Seeds and plant shoots have been studied in laboratories *in vitro* as a model for cellular processes for many decades. More than 40 studies of this type were identified for this review in which the effects of 50-60Hz applied electric current, electric fields, or magnetic fields were investigated. Unfortunately, these studies do not provide information useful to assessing the potential effects of EMF on field crops because the nature and conditions of exposure are not directly relevant to agricultural conditions. For example, the application of strong electric currents directly to seeds or shoots does not replicate the exposure of plants in a field near a transmission line. Seeds and early shoots have limited exposure to electric fields from power lines whilst underground. Even 2.5 centimetres of earth will reduce the electric field by a factor of more than 100 for very dry soil and more than 6.5 million for wet soil. The earth does not shield seeds from the magnetic field, but the strengths of the magnetic fields applied in most all of these studies ranged from about 2- to 20,000-fold higher (with more studies at the higher end of this range) than EirGrid reports directly under a 400 kV transmission line. Nevertheless, although the results of these studies were not very consistent, increased germination and growth of exposed plants are reported in many of these studies.

Experimental studies more relevant to the assessment of EMF from transmission lines on plants are those undertaken in environmentally-controlled greenhouses or growth chambers. As opposed to *in vitro* studies, these studies assess the potential effects of EMF on the growth and development of plants, including commercial crop plants under conditions more similar to those encountered in agriculture.

Pilot studies at Hazelton Laboratories in the State of Virginia in the United States in 1970 explored the early response of corn, buckwheat, and sunflower seeds to combined electric fields and magnetic fields at both lower (10V/m; 100µT) and higher (20V/m; 200µT) levels at both 45Hz and 75Hz (Coate, 1975). No dose-related responses were reported on viability or growth of any of the three seed types, but lowered growth of sunflowers altogether under all exposure treatments was reported. Full follow up studies conducted in a laboratory at the Illinois Institute of Technology and in a greenhouse at the University of Chicago (Rosenthal, 1975) could not replicate the pilot study finding. Under their conditions, Rosenthal et al. reported no overall effects on germination and early sunflower growth, stem length, or chlorophyll content. The author concluded "we have not observed any sunflower trait which appears regularly and clearly affected by the electromagnetic environments imposed in these experiments" (p. 31).

A research program at Pennsylvania State University in the United States performed exploratory studies on 74 species of green plants including food, fiber, and feed crops, weeds, native plants, and several tree species (Bankoske et al., 1976; McKee et al., 1978). The main focus was field alfalfa, field corn, and red winter wheat. Plants were exposed to 60Hz electric fields up to 50kV/m or to control conditions (achieved by screening the plants from the electric field by a grounded-screen Faraday cage). The investigators reported no differences in the dry weights of plants from these groups (McKee et al., 1978) or any tissue damage, except when the applied electric field exceeded 20-25kV/m. The damage was limited to the sharp points or tips of the plants; damage was not noted on other parts of the plant and the plants were reported to continue to grow and flower normally. This observation is consistent with an earlier study by Murr (1963) who analyzed the damage to the tips of orchard grass grown under direct current (DC) electric fields of 40kV/m.

Subsequently, a larger, better-controlled, study was carried out by these investigators at Pennsylvania State University and described in detail (McKee, 1985). The study of five plant species was conducted over 2 years in a large greenhouse in which plants were exposed to uniform electric fields or to field-free conditions in two concurrent replications. The electric field, air temperature, relative humidity, carbon dioxide, and light were monitored. The exposure conditions are summarised in Table 1.

Table 1. Summary of intensity and duration of exposure of plant species to 60Hz electric field (McKee, 1985)

Plant Species	Electric Field (kV/m)		Duration of Exposure (days)
	Exposed Plants	Control Plants	
Alfalfa	30-32	0	74
Tall fescue	12-14	0	93
Sweet corn	30-43	0	91
Soft red winter wheat	30-35	0	112
Hard red spring wheat	10-13	0	112

The exposures of tall fescue and hard red spring wheat were lower than for the other crops to simulate exposures expected under a 765 kV transmission line.

Extensive measurements were made of plant growth and composition including:

- Seed germination
- Seedling growth and establishment
- Vegetative growth
- Reproductive growth
- Flowering
- Seed set
- Seed maturation
- Germination of seed produced on exposed plants
- Biomass production
- Nodulation and nitrogen fixation (alfalfa)
- Feed quality
- Forage content of 11 essential elements
- Leaf area
- Longevity

No statistically significant differences in any of the above measures were reported indicating neither an adverse nor a beneficial effect of exposure to electric fields. Minor but statistically significant differences in plant height were observed in crops grown in different parts of the greenhouse, but neither exposed plants nor control plants were favored. A consistent observation, however, was that plants in electric fields above 30kV/m incurred limited damage (< 2 millimetres) only to the sharp tips of leaves, awns, etc. (<1% of leaf tissue), particularly in sweet corn and soft red winter wheat. The tips of tall fescue and hard red spring wheat of average height were not affected, but the few tallest plants, which experienced higher electric fields, approaching 20-25kV/m, did show discoloration and effects indicative of higher field exposure as reported by McKee et al. (1978).

Smith et al. (1993) reported preliminary experiments in which they exposed radish seeds to AC or AC and DC magnetic fields in four groups and recorded the time to germination. After 21 days the plant height, weight of the root and upper plant, stem diameter, leaf length, and width were measured and the ratio length/width was computed. One group was exposed to a 40μT, 60Hz magnetic field and a 0Hz DC geomagnetic field; a second group was exposed to a 40μT 60Hz magnetic field and a DC magnetic field of 78.3μT along the x-axis; the third group was exposed to a 40μT 60Hz magnetic field and a DC magnetic field of 153.3μT along the x-axis; and the fourth group was an unexposed control group. The authors reported that measured aspects of plants exposed to the AC magnetic field alone did not differ from control plants except for a 25% increase in root weight of the seeds exposed to the AC magnetic field alone. Delays in germination and increased plant height, weight, stem diameter, root weight and leaf length were reported for plants exposed to AC magnetic fields + a 78.3μT DC field, whereas generally opposite or no effects were reported for these parameters except root weight when the DC magnetic field was increased to 153.3μT.[4] The purpose of the study was to test the hypothesis that AC magnetic fields produced biological effects only when aligned with DC magnetic fields of certain intensities. While the authors expressed the opinion that the results were consistent with their hypothesis, they state "[t]hese preliminary studies do not reveal what is responsible for the effects seen" (p. 74). The intensities of the DC magnetic field tested are considerably higher than the ambient DC geomagnetic field in Ireland, which is ~ 49μT.

Subsequently, Davies (1996) compared radish, mustard, and barley seeds exposed to control conditions or to one of the AC-DC field combinations (40μT 60Hz magnetic field + 78.3μT DC field) applied by Smith et al. The measurements of the mustard and barley plants in control and exposed groups did not differ. Differences were reported in three experiments for radish plants with increased dry stem weight and plant height in exposed plants with other parameters less consistently affected, which Davies interpreted as a partial replication of the Smith et al. study. Parkinson (1997) criticised the Davies study for its poor control over experimental variation and

[4] A study of *in vitro* exposures of barley seeds exposed for 5 days has reported that a 0.5μT, 50Hz magnetic field applied in parallel to a DC magnetic field at 65.8μT caused less water loss and shorter shoot lengths compared to control conditions. When combined with DC magnetic fields of 55, 60, 70, and 76μT, however, the 50Hz magnetic field had no significant effect on shoot growth or formation of photosynthetic pigments. While this finding would appear to support the Smith et al. hypothesis, it has not been replicated and has no practical significance with regard to predicting effects of 50Hz magnetic fields on plants in Ireland where the DC magnetic field is ~49μT.

aspects of the statistical analyses to which Davies replied (Davies, 1997), but his arguments are not convincing. Potts et al. (1997) also repeated the Smith et al. study under the conditions Smith et al. reported, but these investigators were unable to confirm any effect of combined AC and DC magnetic fields (40μT 60Hz magnetic field and a DC magnetic field of 78.3μT) on 15 developmental parameters that they measured to characterise the growth of radish seedlings.

A study of strawberry plants raised in a greenhouse at Atatürk University in Turkey reported that plants exposed to 50Hz magnetic fields at 96mT showed an 18% increase in the strawberry yield per plant, had no effect at a 192 mT exposure level, and decreased strawberry yield by 3% with exposure to 384mT (Eşitken and Turan, 2004). Average fruit weight increased very slightly in plants exposed to 96mT, 192 mT, and 384mT relative to the control groups. In addition, small increases and decreases in 11 chemical components of the strawberries were reported across the exposure conditions. The authors stated that their study suggests the application of magnetic fields had benefits on strawberry yield and some components of the strawberries' nutrition. The practical relevance of these findings, however, is unclear as the lowest applied magnetic field was almost 20,000-fold higher than the magnetic field that could be experienced under a 400 kV transmission line.

Summary and Conclusions

A large scientific literature has accumulated since the 1970s investigating potential environmental and health effects of ELF EMF. Most of the scientific research has focused on human health effects. As part of human health risk assessments, the relevant scientific literature has been repeatedly and systematically reviewed by a number of international and national health, scientific, and government agencies. Perhaps most notably, based on its comprehensive review of the relevant research results, the WHO concluded that the available evidence does not confirm the existence of any health consequences from exposure to ELF EMF (WHO, 2007). Known adverse effects, such as nerve and muscle stimulation, which are temporary and reversible, may occur at high exposure levels, at levels much higher than that could be experienced even directly under 400 kV transmission lines. Current relevant exposure guidelines applicable in Ireland are stated by the WHO to provide adequate protection for all known effects. Although these guidelines are intended to protect humans against potential adverse effects, **there is no evidence to suggest that this protection would not apply to farm animals.**

Economic considerations have led to a considerable amount of scientific research, although less systematic in nature, on the potential effects of ELF EMF on livestock and crops. The research studies on livestock tended to focus on species with sizable economic impact, such as cattle, sheep, and swine, and concentrated on outcomes of reproduction, milk production, and growth. ELF EMF research related to plants was even less consistent. Although sporadic associations with various measures from some of the studies on animals and plants were reported, overall, no consistent or convincing pattern of any harmful effects of ELF EMF has emerged in either livestock or crops that would have relevance to farm operations around 400 kV transmission lines in Ireland or even transmission lines operating at some higher voltages elsewhere.

While electric fields potentially may result in perception by animals under 400 kV transmission lines, research does not indicate that exposure to electric fields results in adverse effects in animal health, productivity, or reproduction. Magnetic-field levels that could be encountered around 400 kV transmission lines have no consistently demonstrated adverse effects, even if dosimetric differences due to anatomical and size differences are considered between farm animals, humans, and laboratory animal species, such as rodents.

Among farm animals, cattle have been the most investigated species in the ELF EMF literature. Farm surveys and field observation of grazing cattle conducted mostly in the United States and Sweden reported no consistent differences in behaviour or productivity between farms intersected by high-voltage transmission lines (ranging between 380 kV and 765 kV) and farms away from transmission lines. Following a suggestion that cattle may tend to naturally orient themselves in the north-south direction, which orientation may be affected by power lines, several studies, mostly examining low-quality satellite imagery, investigated cattle orientation and reported inconsistent results. A series of well-designed experiments in Québec examined various behavioural, reproductive, and productivity parameter in dairy cattle in response to exposure to electric fields (up to 10kV/m) and magnetic fields (up to 30μT) separately and in combination. While some of the studies reported small differences (a few percentages) in some of the parameters investigated (e.g., feed intake, length of oestrus cycle), all of these differences appeared to be within physiological ranges and showed no consistent pattern. There were no consistent differences in various measures of milk yield (e.g., fat corrected milk yield, fat yield, protein yield), hormone concentrations (e.g., melatonin, prolactin, thyroxine), or neurotransmitter concentrations in the cerebrospinal fluid.

Several experimental studies of sheep have investigated immunological parameters (IL-1 and IL-2 concentrations) and hormone concentrations (melatonin, cortisol) in animals housed under a 500 kV transmission line, and reported no consistent differences when comparisons were made to sheep housed away from the high-voltage lines. No differences were reported in tumour development in sheep in a study, which compared animals housed under a 345 kV line to animals housed away from the line.

A study of potential effects of a 345 kV line in swine reported no statistically significant results in behaviour, productivity (e.g., backfat thickness, carcass quality) or effects in the offspring between exposed and unexposed animals. Avoidance of very high electric fields (30kV/m) was reported in miniature swine. These electric fields, however, are significantly higher than fields that could be encountered under a 400 kV or even a 765 kV transmission line. A multi-generation study of miniature swine showed inconsistent results when examining developmental effects due to 30kV/m electric fields.

While a farm survey that included horses reported no impact on them, horses were not a subject of experimental studies of EMF. Growth, fertility, and behaviour of chickens were investigated in a small number of studies, but no consistent effects of ELF EMF were reported.

There is a long history of agricultural experimentation to assess the effects of electricity or EMF on crops. Field studies of crop responses to 1100 kV test lines that produce electric fields far greater than 400 kV and lower transmission lines and field studies of operating 380 kV and 500 kV transmission lines that produce both electric and magnetic fields were reviewed. These studies included field observations of peas, barley, alfalfa, grasses, corn, and wheat over multiple years, and single-year field studies of onions, rice, soybeans, and cotton. Comparisons of exposed and unexposed crops in these studies did not indicate that EMF exposures caused adverse or beneficial effects on crop growth or yield. A variety of other potential environmental factors including weather, microclimate, and soils were identified as the source of sporadic differences between crop plants located under or around test and transmission lines. In the one study where a reduction in cotton yield of plants under a 500 kV line during one season was observed, the cause was not determined. A 5-year study of crops around a 380 kV transmission line, where the highest field levels were 3.9kV/m and 4.5µT, did not report impaired crop performance. Hence, field studies do not report that EMF at levels associated with 400 kV transmission lines harm crop plants of any species studied.

Most experimental *in vitro* studies of EMF effects on crop seeds and shoots in the laboratory involved exposures and conditions that have little or no relevance to exposures that crops experience near transmission lines. This lack of relevance derives from the type of exposure applied and the often astonishingly high fields applied. In contrast, the few research studies that exposed alfalfa, field corn, winter wheat, and spring wheat to electric fields in greenhouses, however, did study more relevant exposures at levels closer to those produced by transmission lines, albeit those operating at 765 kV and 1100 kV. In addition, the greenhouse environment allows for better control of potentially confounding factors, and so provides better models from which to predict effects in the agricultural environment. These studies did not report adverse effects of high electric field exposures on these crops except for damage to the sharp tips of leaves of some crops for exposures to electric fields generally above 20-25kV/m. Several laboratory studies examined the effects of 50 or 60Hz magnetic fields on plant growth. No effects on corn, buckwheat, or sunflowers could be confirmed at 100 and 200μT. No effects of 40μT 60Hz magnetic fields on mustard or barley seed growth were observed. Two laboratories attempted to replicate a single report of increased growth of radish seeds, but the results were mixed; a partial replication claimed by one laboratory and a total failure to replicate by the other. These latter laboratory studies, which concern specific intensities and orientation of the DC magnetic field to ELF fields, are of scientific interest but do not have any direct relevance to the assessment of potential effects of EMF from transmission lines on crop performance or health.

Together this review of field and experimental studies of crops exposed to electric fields, magnetic fields, or both does not provide any reliable evidence for effects that would be harmful to crop yield or production, even for test lines operating at voltages up to 1100 kV. The levels of electric fields associated with transmission lines at voltages up to 400 kV have not been reported to produce even minor damage to plants.

In conclusion, the available scientific evidence summarised in the current report does not provide consistent or convincing evidence that either electric or magnetic fields associated with the Irish electric transmission system may adversely affect the livestock or crops produced on Irish farmlands.

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Limitations

At the request of EirGrid plc, Exponent summarised research on the potential effects of electric and magnetic fields on livestock and crops. This report summarises work performed to date and presents the findings resulting from that work. In the analysis, we have relied on published scientific research and agency reports. The findings presented herein are made to a reasonable degree of engineering and scientific certainty. Exponent reserves the right to supplement this report and to expand or modify opinions based on review of additional material as it becomes available, through any additional work, or review of additional work performed by others.

The scope of services performed during this investigation may not adequately address the needs of others than the intended users of this report, and any re-use of this report or its findings, conclusions, or recommendations presented herein for other purposes is at the sole risk of the user. The opinions and comments formulated during this assessment are based on observations and information available at the time of the investigation. No guarantee or warranty as to future life or performance of any reviewed condition is expressed or implied.

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