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Landscape changes at Chernobyl

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Mestrado em Ecologia e Ambiente

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Todas as correções determinadas pelo júri, e só essas, foram efetuadas.

O Presidente do Júri,

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Resumo

A vida de muitas pessoas mudou há trinta e dois anos atrás, aquando do acidente nuclear de Chernobyl, onde um dos reatores nucleares explodiu durante um teste de segurança. Com a explosão, grandes quantidades de materiais radioativos como cézio, estrôncio e plutónio foram libertados para a atmosfera. Doses elevadas de radiação causaram danos severos no ADN dos organismos vivos, tendo impacto direto nas mudanças sofridas pelo meio ambiente, tanto ao causar morte em poucos segundos como alterando as capacidades biológicas da biota local. À medida que a população humana das áreas adjacentes foi sendo evacuada, os terrenos foram abandonados, levando também a alterações no meio cujo efeito é ainda desconhecido. Este trabalho teve como objetivo analisar o estado da produção primária da vegetação na Zona de Exclusão de Chernobyl depois do acidente, comparando com o seu estado anterior. Através de medições de radiação e da avaliação do Índice de Vegetação por Diferença Normalizada (NDVI), pretendeu-se determinar a relação entre estas duas variáveis, através de ANOVAs e Modelos Aditivos Generalizados (GAM), no sentido de melhor compreender como é que a vegetação reagiu à radiação libertada no acidente. Usando dados de deteção remota, fez-se uso de imagens obtidas pelos satélites Landsat, bem como áreas amostradas no terreno. Os resultados obtidos mostram que o NDVI foi aumentando ao longo dos anos depois do acidente e que é independente da atual radiação registada. Isto sugere que até certo nível de exposição à radiação, os efeitos positivos do abandono do território e/ou a reduzida abundância de espécies herbívoras causada pela radiação superam os efeitos negativos de longo prazo que a radiação provoca na vegetação. Contudo, a partir de certo nível de exposição à radiação, espera-se que a produção primária seja negativamente afetada.

Palavras-chave: Zona de Exclusão de Chernobyl, Radiação, Vegetação, Índice de Vegetação por Diferença Normalizada, Deteção Remota

Abstract

Thirty-two years ago, the Chernobyl nuclear accident changed the lives of many people, when one of the nuclear reactors exploded during a safety test. The explosion released huge amounts of radioactive materials like caesium, strontium, and plutonium into the atmosphere. High doses of radiation caused severe damage to the DNA of living beings, with direct impact on the changes suffered by the environment, either by causing instant death or by altering the fitness of the local biota. As people were evacuated from the surrounding areas, the land was left abandoned and the indirect changes caused by the alteration of land use are still unknown. Thus, the objective of this study was to analyse the state of primary production of the vegetation in the Chernobyl Exclusion Zone after the accident, comparing with its previous state. Through Normalized Difference Vegetation Index (NDVI) and radiation measurements, the relationship between these variables was assessed using Analysis of Variance (ANOVA) and Generalized Additive Models (GAM), to understand how the vegetation responded to the radiation exposure. The data was obtained through remote sensing, using available Landsat satellite imagery and sampled areas registered on the field. The results show that the NDVI increased over the years after the accident and that it is independent of the current radiation measured. This suggests that to some level of radiation exposure, the positive effects of land abandonment and/or the negative effects of radiation on abundance of herbivore species surpass the long term negative effects of radiation exposure on the vegetation. Nonetheless, above some radiation threshold level, primary production is expected to be negatively affected.

Keywords: Chernobyl Exclusion Zone, Radiation, Vegetation, Normalized Difference Vegetation Index, Remote sensing

Table of Contents

1. Introduction	1
1.1 Nuclear energy.....	1
1.2 The Chernobyl Nuclear Disaster	3
1.3 Radiation	6
1.4 Impact on human population	7
1.5 Impact on agriculture.....	9
1.6 Impact on flora and fauna.....	10
1.7 Impact on water bodies.....	11
1.8 Adaptation.....	11
1.9 Remote sensing	12
1.10 Objectives:	13
2. Materials & Methods.....	14
2.1 Field work.....	17
2.2 Cloud Masking	20
2.3 Seasonal datasets	21
2.4 Hypothesis Testing	23
3. Results.....	23
3.1 NDVI variance between groups.....	23
3.2 NDVI and radiation relationship.....	30
4. Discussion.....	35
4.1 NDVI variance between groups.....	35
4.2 NDVI and radiation relationship.....	37
5. Conclusion	40
References	42
Appendix I.....	48
Appendix II	52
Appendix III	56

List of Tables

Table 1- Landsat satellites and respective bands selected for use.	15
Table 2 - List of vegetation classes analysed and their samples (features) number.	18
Table 3 - Number of obtained satellite images per season dataset and year.....	21
Table 4 - Distribution of years through different groups.	22
Table 5 – ANOVA and Kruskal-Wallis test results for all vegetation classes of the Foliage season dataset to assess the NDVI variance between groups of years.....	24
Table 6 – ANOVA and Kruskal-Wallis test results for all vegetation classes of the No-Foliage season dataset to assess the NDVI variance between groups of years.	25
Table 7 - p-values of the pairwise t-test for all classes of vegetation of the Foliage season dataset.....	27
Table 8 - p-values of the pairwise t-test for all classes of the No-Foliage season.	28
Table 9 – Descriptive NDVI statistics of each group of the Foliage season	30
Table 10 – Descriptive NDVI statistics of each group of the No-Foliage season.....	30
Table 11 - Results of the GAM test to assess the relationship between NDVI as function of radiation.....	32
Table 12 - Statistics of radiation values for each class of vegetation	32

List of Figures

Figure 1 - Location of the Chernobyl's nuclear power plant reactor 4 (Adapted from Bing Maps).....	1
Figure 2 - Schematic design of the nuclear reactor (by Stefan Riepl, accessed: Sep 2018)..	2
Figure 3 - The abandoned city of Pripyat in 2012 (by Michael Kötter, accessed: Sep 2018)..	4
Figure 4 - Sarcophagus enclosing the damaged building of the reactor nº 4 (by Carl Montgomery, accessed: Sep 2018).....	5
Figure 5 - The NSC already covering the reactor building (by Tim Porter, accessed: Sep 2018).	5
Figure 6 - Alpha, beta and gamma particles of ionizing radiation (by world-nuclear.org, accessed: Sep 2018).	6
Figure 7 - Comparative whole-body radiation doses (by world-nuclear.org, accessed: Sep 2018).	7
Figure 8 - INES rating scale (by iaea.org, accessed: Sep 2018).	9
Figure 9 - The polygon (in brown) for cropping the target area from the images. The CEZ border appears in red and the sample locations are the little points in black inside the CEZ.	16
Figure 10 - The cropped target area with the CEZ border in red.	17
Figure 11 – Close-up of 3 sampled locations (yellow) inside the CEZ and a nearby road (blue).	18
Figure 12 - Boxplot taking all classes of vegetation together for the Foliage dataset, showing the differences of NDVI values between groups of years (NDVI~Group). Group 1 (1984-1986); Group 2 (1986-1986); Group 3 (1986-1990); Group 4 (1990-2017).....	25
Figure 13 - Boxplot taking all classes of vegetation together for the No-Foliage dataset showing the differences of NDVI values between groups of years (NDVI~Group). Group 1 (1984-1986); Group 2 (1986-1986); Group 3 (1986-1990); Group 4 (1990-2017).....	26
Figure 14 - Linear model plot for all classes with untransformed data (LM model: NDVI~Radiation).....	31
Figure 15 - Linear model plot for all classes after a logarithmic transformation of the data (LM model: log(NDVI)~log(Radiation)).	31

List of Abbreviations

ANOVA – Analysis of Variance

ARS – Acute Radiation Syndrome

BWR – Boiling Water Reactor

CEZ – Chernobyl Exclusion Zone

CRS – Coordinate Reference System

DOS – Dark Object Subtraction

EPSG – European Petroleum Survey Group

ESA – European Space Agency

ETM+ – Enhanced Thematic Mapper Plus

GAM – Generalized Additive Model

GIS – Geographic Information System

GPS – Global Positioning System

IGS – International Ground Stations

INES – International Nuclear and Radiological Event Scale

KML – Keyhole Markup Language

LGAC - Landsat Global Archive Consolidation

LPGS - Landsat Product Generation System

LWGR – Light Water Graphite Reactor

NDVI – Normalized Difference Vegetation Index

NIR – Near-Infrared

NSC – New Safe Confinement

OLI – Operational Land Imager

PWR – Pressurized Water Reactor

RBMK - Реактор Болшой Мощности Канальный (High-power Channel Reactor)

ROS – Reactive Oxygen Species

SCP – Semi-Automatic Classification Plugin

SI – International System of Units

SWIR – Shortwave Infrared

TM – Thematic Mapper

USGS – United States Geological Survey

UTM – Universal Transverse Mercator

UV – Ultraviolet

WGS – World Geodetic System

1. Introduction

Nuclear accidents have always been a cause of utmost public concern and yet there is still too much to be acknowledged regarding its effects from an ecological point of view (Møller and Mousseau 2007; Møller and Mousseau 2009; Moller and Mousseau 2013; Mousseau et al. 2013). Although the number of major accidents is low, they have such a great impact that they are object of discussion and study for decades after. Such is the case for the Chernobyl Nuclear Disaster which occurred on 26 April 1986 in the former Soviet Union (now Ukraine) (Figure 1), when reactor nº 4 of the Chernobyl nuclear power plant exploded during a safety test that was being carried out during a maintenance shutdown.

Figure 1 - Location of the Chernobyl's nuclear power plant reactor 4 (Adapted from Bing Maps).

1.1 Nuclear energy

Nuclear reactors produce and control the release of energy from splitting the atoms of uranium (nuclear fission) (world-nuclear.org). This generates heat that boils water leading to the formation of steam, which in turn drives turbogenerators, producing electricity (world-nuclear.org).

During the early 1950s, two main reactor designs emerged and are still in use today. The pressurised water reactor (PWR) and the boiling water reactor (BWR). They differ in the way

they produce steam but both use water as coolant and as moderator (slows down neutrons originated from fission so they can create more fission) (world-nuclear.org). Other reactor designs were developed, being the one used at the Chernobyl nuclear power plant one of them, the Soviet-designed RBMK (reaktor bolshoy moshchnosti kanalny, high-power channel reactor)(Figure 2).

The RBMK reactor model is a light water graphite reactor (LWGR) and uses water as coolant and graphite as moderator. Its design diverged from many other nuclear reactors as it was meant principally for plutonium production and power production (world-nuclear.org). As it was cheaper, faster to build and capable of achieving high power generation, it was widely used by the former Soviet Union during the Cold War. The drawback is the fact that the reactor characteristics, particularly the control rod design and the positive void coefficient are unsafe (world-nuclear.org). The control rods are devices that directly control the nuclear reaction and can be used to immediately stop such reaction. The positive void coefficient can be translated as a positive feedback loop of the chain reaction that is extremely dangerous. When the power begins to increase, more steam is produced, which in turn leads to an increase in power. The extra heat resulting from the increase in power raises the temperature in the cooling circuit and more steam is produced. The additional steam leads to less cooling and less neutron absorption, resulting in a rapid increase in power, capable of reaching 100 times the reactor capacity (world-nuclear.org). This type of reactor was never built outside the Soviet Union and its design was abandoned after the Chernobyl accident.

Figure 2 - Schematic design of the nuclear reactor (by [Stefan Riepl](#), accessed: Sep 2018).

1.2 The Chernobyl Nuclear Disaster

As in any other nuclear reactor, a coolant (usually water) needs to be actively pumped inside to keep the reactor cooled, even after an emergency shutdown of the nuclear chain reaction inside the reactor. Even after the chain reaction stops, decay heat continues to irradiate from the core, and it can lead to the reactor meltdown if not cooled. In case of a total blackout, the Chernobyl's reactors had three backup diesel generators that could start up in 15 seconds, but not fast enough to attain full power output as it took 65 to 70 seconds to reach the 5.5-megawatt (MW) required to power one main water pump (Labib 2014).

As the station lacked an important safety feature, that is, the uninterrupted supply of energy to the coolant pumping system in case of an external power loss, the objective of this safety test was then to simulate a power loss and verify if the rotational energy from the steam turbines that were winding down (after a power loss) could maintain the cooling pumps running until the backup generators could start to provide the required power to the pumps themselves (Labib 2014). Preparations for the test started on 25th April with the disablement of emergency cooling systems and, even though the test was meant to be carried out by the day shift personnel, due to an unexpected postponing, the test was conducted by the less prepared night shift of the subsequent day, 26th April.

There were two main causes that together led to the accident: (1) the unfollowed test protocol by the operators at the site (disregarding safety parameters) and, (2) a reactor design flaw of the RBMK model, which ultimately caused an unexpected increase in steam pressure inside the reactor and consequent explosions.

Because of some problems inherent to the chemical processes of the nuclear chain reaction, the test was conducted on an unstable reactor configuration contrary to what was specified in the test protocol, as the operators disregarded some safety parameters so there would be no delays to the test schedule (Labib 2014). During the test the reactor was supposed to be running at a low power level, between 700 MW and 800 MW, but due to reactor poisoning (core power decreases without further operator action) by xenon-135, which is a fission by-product, the reactor reached power levels of near-shutdown state (30 MW) (Labib 2014). To counteract this, the operators disabled the automatic system of the control rods and manually extracted the majority of the control rods that were limiting the nuclear reaction, while also reducing the reactor coolant pumping (Labib 2014). The test resumed, the run-down of the turbine generator started and the diesel generators were turned on. While these diesel generators were starting to pick up the pumps, as the momentum of the turbine generator decreased, so did the power it produced for the pumps, leading to a decrease in water flow and increased formation of steam bubbles in the core (Labib 2014).

Power increased due to the positive void coefficient and in the last moments of the test, as the operators tried to stop the nuclear reaction, the reactor experienced a severe thermal power spike caused by the manual insertion of the graphite control rods (made to shut down the reactor) that momentarily had the reverse effect (control rod flaw). The graphite in the control rods led to a power surge and caused the first steam explosion. It was then followed by a second explosion, seconds after, that completely destroyed the reactor and stopped its reaction (Labib 2014). With this explosion, the reactor containment vessel was breached and caught fire, where ejected graphite, nuclear fuel and other by-products of the nuclear fission were exposed, releasing extreme levels of radiation to the atmosphere and the surroundings.

Pripyat city, now abandoned (Figure 3), which was the home for the families and workers of the power plant and located near it, was only evacuated 24 hours later. At the time of the accident, the authorities responsible for the plant were late to recognise what had happened and an official report was delayed, which endangered not only the civilians living in the surroundings of the plant as well its own workers. Emergency response teams, such as firemen, were also not informed of the danger of the situation and did not wear protective gear against such high doses of radiation being released from the on-burning reactor building (Labib 2014). Some people suffered from acute radiation syndrome (ARS) and died days after, while others developed cancers (mainly thyroid cancer). Acute radiation syndrome is a clinical scenario characterized by a complex of acute deterministic effects affecting various organs and body functions in the irradiated person (OECD-NEA, 2002).

Figure 3 - The abandoned city of Pripyat in 2012 (by [Michael Kötter](#), accessed: Sep 2018).

It was feared that another explosion could take place, if the melting fuel passed through the floor and reached the basement levels under the reactor, which were flooded with water (Labib 2014). As there was a risk of a bigger steam explosion, some volunteers underwent a

suicide mission to drain water from those levels and prevent an even worse accident. Although they were successful, all died sometime after.

After the fires were extinguished, the exposed reactor and nuclear fuel needed to be enclosed, and so, bags filled with sand and other materials such as lead and boric acid were dropped inside the reactor building by helicopter (Labib 2014). It was only by December 1986 that a concrete sarcophagus (Figure 4) was built to completely isolate all radioactive material and debris originated from the accident.

Figure 4 - Sarcophagus enclosing the damaged building of the reactor nº 4 (by [Carl Montgomery](#), accessed: Sep 2018).

By October 2017, the New Safe Confinement (NSC) (Figure 5) structure was finally built next to the reactor and then slid over the entirety of the reactor nº4 building, preventing any more releases of radiation and protecting the station from external threats. It has a lifetime of a minimum of 100 years ([ebrd.com](#)).

Figure 5 - The NSC already covering the reactor building (by [Tim Porter](#), accessed: Sep 2018).

1.3 Radiation

Radiation can be defined as energy travelling through space. Its forms can range from ultraviolet (UV) to radio communications and are common in our daily lives, but we can divide it in two types of radiation: ionizing and non-ionizing radiation. Ionizing radiation can be dangerous as it has sufficient energy to remove tightly bound electrons from atoms, creating ions capable of breaking chemical bonds and causing ionization of the matter through which it passes (world-nuclear.org). The energy from non-ionizing radiation can move atoms but cannot create ions.

Regarding emissions, ionizing radiation can then be divided in alpha, beta and gamma radiation (Figure 6) and each has different penetrating power and energy.

Figure 6 - Alpha, beta and gamma particles of ionizing radiation (by world-nuclear.org, accessed: Sep 2018).

Radiation is measured in Becquerel (Bq) which is an International System of Units (SI) derived unit of radioactivity and one Becquerel can be defined as the activity of a quantity of radioactive material in which one nucleus decays per second (world-nuclear.org).

Regarding the amount of ionizing radiation absorbed in tissue, Gray (Gy) units can be used to express the quantity of absorbed dose to the thyroid while Sievert (Sv) express the doses to the whole body from both external and internal irradiation in terms of weighted quantity, effective dose (Nations and Scientific Committee 2010). As a comparison (Figure 7), the annual average effective dose from natural background radiation is 2.4 mSv, while a typical effective dose from a medical CT scan is of the order of 10 mSv (Nations and Scientific Committee 2010).

Figure 7 - Comparative whole-body radiation doses (by world-nuclear.org, accessed: Sep 2018).

1.4 Impact on human population

The human impact of the accident is still felt today with thousands of cancers being attributed to the radioactive fallout (Labib 2014) and the fact that the 30 km wide Chernobyl Exclusion Zone (CEZ) created after the accident is still off-limits regarding human inhabitation. By Ukrainian Law, no economic activities are authorized in the CEZ for it is classified as a contaminated area and separated from adjacent territories (Bondarkov et al. 2011).

The consequences were much severe immediately following the accident where 237 people (mostly emergency response workers) were reported to have suffered from acute radiation sickness from which 31 died in the first three months (OECD-NEA, 2002; Labib 2014).

The doses these workers received from external irradiation ranged from 1 to 16 Sv while doses from internal irradiation ranged up to 20 Gy (OECD-NEA, 2002). As reference, the whole-body exposure threshold for ARS is 500 mGy (Institute of Medicine, 1997). After the initial emergency response to put the fires out, clean-up operations took place from 1986 to 1990 and involved around 600,000 liquidators (workers for the clean-up process) (OECD-NEA, 2002). These liquidators could only work at the site for about 40 seconds even with protective gear, as they would have already reached their official lifetime limits of radiation exposure (Labib 2014).

Amidst the unaware civilian exposure to radiation, there were no cases of ARS among the general public, where a total of 160,000 people living in the 30 km area around the plant (CEZ) were evacuated from (OECD-NEA, 2002; Nations and Scientific Committee 2010). Ionizing radiation directly increases the frequency of chromosome breakage and also indirectly causes DNA mutations via oxidative stress (Møller and Mousseau 2016). It is most damaging to cells that are actively dividing, and because adult mammals' cell division is slow, except for hair follicles, skin, bone marrow and the gastrointestinal tract, vomiting and hair loss are usually the symptoms of ARS (Labib 2014). There are two main pathways of exposure suffered by the population: the radiation dose to the thyroid gland as a result of the concentration of radioiodine and other similar radionuclides; and the whole-body dose mainly caused by external irradiation of radiocaesium (OECD-NEA, 2002).

Besides the direct radiation-induced problems, another major health effect of the accident was the anxiety and distress on the population, which trauma resulted in changes in diet, smoking and alcohol consumption and even in an increase in voluntary abortions and suicides, which are unrelated to the radiation exposure but the fear of it (Nations and Scientific Committee 2010).

The Chernobyl nuclear disaster was rated level 7 by the International Nuclear and Radiological Event Scale (INES) (Figure 8). The only other nuclear accident of the same scale to have happened was the most recent Fukushima nuclear disaster in 2011. Three parameters are taken into account upon selecting a level for a given event: whether people or the environment have been affected; whether any of the barriers to the release of radiation have been breached; whether any of the layers of the safety systems are breached (Labib and Harris 2015).

Figure 8 - INES rating scale (by iaea.org, accessed: Sep 2018).

1.5 Impact on agriculture

With the release of fission products such as caesium, iodine and strontium, which have high nuclear decay rates, bioaccumulation on both land and water bodies became one of the main causes of concern (Kryshev 1995; OECD-NEA, 2002; International Atomic Energy Agency 2008).

The release of radiation was so massive, around 10 EBq (10^{19} Bq) (Evangelidou et al. 2016), that these products were soon detected by nuclear facilities in Scandinavian countries, even before the Soviet Union officially reported the accident (Nations and Scientific Committee 2010).

Agricultural land is still excluded from use and will continue to be for a long time, being the direct deposition of radionuclides on plants a major source of contamination of it. Several restrictions for agricultural and farm animal production were imposed after the accident, as to prevent public health problems derived from the intake of contaminated products (OECD-NEA, 2002). This was even applied to central European countries that were reached by the fallout, contaminating the land in which the cattle feed upon.

Countermeasures to avoid human exposure often have to be imposed immediately after an accident, even before the levels of contamination are known, and include the cessation of field work, consumption of fresh vegetables, pasturing of animals and poultry and also the introduction of uncontaminated forage. Since these measures were not immediately applied

after the accident on the Chernobyl power plant, the doses to humans were enhanced (OECD-NEA, 2002).

1.6 Impact on flora and fauna

According to official reports, the forest environment has showed a particularly high uptake of radiocaesium (International Atomic Energy Agency 2008) mainly because of the high filtering characteristics of trees (tree canopies). Tree contamination was mainly caused by direct interception of radiocaesium by the tree canopy, which intercepted about 60% to 90% of the initial deposition (International Atomic Energy Agency 2008). Moreover, the high organic content and stability of the forest soil increases the transfer of soil-to-plant radionuclides, resulting in lichens, mosses and mushrooms exhibiting high concentrations of these radionuclides (OECD-NEA, 2002).

The nearest forest (5 km² area) located southwest of the nuclear plant turned red and died 10 to 20 days after the accident (period of maximum radioactive impact caused by short lived radionuclides (Committee 2001)), then being named as Red Forest. It was a pine forest that received doses up to 100 Gy. As it was necessary to reduce further land contamination and prevent the dispersion of radionuclides by forest fires, remedial measures were undertaken in 1987, where the top 15 cm of soil was removed and dead trees were cut down. Although this was not the ideal clean-up approach (Tikhomirov et al. 1993), the resulting waste was buried and covered with sand in in-situ trenches (Oskolkov et al. 2011), totalling a volume of 100,000 m³, reducing soil contamination by at least a factor of ten (OECD-NEA, 2002).

The long-term impacts on the fauna from low chronic exposure are still unclear, as there are several studies showing negative impacts of ionizing radiation on organisms whilst others have been inconclusive or have shown no impact (Murphy et al. 2011). It has been shown that in highly contaminated areas there has been a decrease on the abundance of mammals (Møller and Mousseau 2013), birds (Møller and Mousseau 2007; Mousseau and Møller 2013) and insects (Møller and Mousseau 2009), while other studies, on limited data, suggest no negative influence of radiation on mammal abundance (Baker and Hamilton 1996; Deryabina et al. 2015). Certainly, more studies should be conducted to better understand the impacts of radiation on fauna.

The flora has also been negatively impacted, with either reduced plant growth (Mousseau et al. 2013; Mousseau et al. 2014; Boratyski et al. 2016) or decreased pollen viability and seed germination rate (Boratyski et al. 2016; Møller et al. 2016; Møller and Mousseau 2017) being

negatively correlated with radiation intensity, suggesting that radiation directly reduced plant fitness.

1.7 Impact on water bodies

The contamination of water bodies was less severe when compared with forest contamination, as it was dominated by short lived radionuclides that sunk and deposited at the bottom of rivers and lakes (Alexander and Dmitri 2008; International Atomic Energy Agency 2008), or diluted into the Black and Mediterranean seas. Although it was determined that the contamination of the water system currently do not pose a public health problem, this system should continue to be monitored to ensure that deposited radionuclides do not washout from the catchment to drinking-water supplies (OECD-NEA, 2002). No evidence was found that the ecological status of lake macroinvertebrate communities are influenced by the contamination from the accident (Murphy et al. 2011). Another recent study (Lerebours et al. 2018) on freshwater systems at Chernobyl showed strong anomalies in the reproductive biology of fishes, but it cannot be determined if they were caused from ongoing chronic low dose radiation exposure or if it originated from higher dose rates on previous generations. Also, it appears that there was no effect on the relative abundance of fish species caused by radiation (Lerebours et al. 2018).

1.8 Adaptation

Despite all the negative impacts, some organisms can still prosper as demonstrated by the presence of radiotrophic melanotic fungi growing in the interior of the Chernobyl damaged power plant (Zhdanova et al. 2000; Labib 2014; Casadevall et al. 2017; Cordero et al. 2017). These fungi are capable of resisting such ionizing radiation and can even use it to grow. Synthesizing melanin and using it to convert gamma radiation into chemical energy, these fungi can thrive even under such extremely hazardous conditions. Melanin mediates radioprotection by absorbing radioactive energy and dissipating it in the form of heat while also limiting and/or neutralizing the generation of cytotoxic reactive oxygen species (ROS) that can damage intracellular molecules (Cordero et al. 2017). This was also demonstrated in another study (Robertson et al. 2012) where ionizing radiation was revealed to not only enhance the growth of a fungus (*Wangiella dermatitidis*) but also increasing its survivability by inducing translesion DNA synthesis (TLS, which is DNA repair mechanism). Melanotic fungi can be also found in remote regions like the Arctic and Antarctic (Dadachova et al. 2007; Labib 2014; Casadevall et al. 2017; Cordero et al. 2017).

Meanwhile, the possible adaptation of organisms living under exposure of low chronic levels of radiation inside the CEZ is starting to being studied. While there is no clear evidence for the existence of hormesis (i.e., superior fitness at low levels of radiation exposure compared with controls and high levels of radiation exposure) related to radiation exposure from the Chernobyl accident, adaptations to radioactive contamination have already been detected (Møller and Mousseau 2016). For example, a Scots pine seed from the 1997 Chernobyl collection showed a higher resistance to acute gamma irradiation in spite of an increased frequency of aberrant cells in the progeny (Boubriak et al. 2016).

Although radiation exposure may have led to negative biological effects at the individual level, the possible positive impacts of field abandonment after the evacuation of the human population from the area could be playing a major role in the apparent flourishing of wild life inside the CEZ (Deryabina et al. 2015). This can be seen by the urban forest succession in the now abandoned city of Pripjat (Laćan et al. 2015). Also, positive community-level species interactions could be taking place, such as facilitation, which could be responsible for the amelioration of environmental stress caused by low-level radiation exposure (Bruno et al. 2003; Qi et al. 2018).

To study the long-term impacts of ionizing radiation exposure and other stresses on the biota, satellite images are used in a technique called remote sensing.

1.9 Remote sensing

Remote sensing is the technique of acquiring information and extracting spectral, spatial and temporal features about objects, areas or phenomenon without coming into physical contact with these objects (Gandhi et al. 2015). This is done using special sensors on board of satellites, airplanes and/or drones that capture images of the Earth's surface.

The use of satellite imagery has been of great importance and a main method used for phenology monitoring (Duarte et al. 2018; Weber et al. 2018; Wu et al. 2018) and change detection of ecology and environment, with an increased application in vegetation research (Song et al. 2001; Xie et al. 2010; Gandhi et al. 2015; Fan and Liu 2016; Brehaut and Danby 2018; Gillespie et al. 2018; Kern et al. 2018; Zhang et al. 2018).

Remote sensing provides a monitoring tool over long time periods (more than 40 years), enabling a better understanding of climate cycles, anomalies and trends, that are usually unable to be perceived under a typical five-year research program (Chasmer et al. 2018). Remote sensing can also overcome some limitations of field surveys, where vegetation data are collected at the species or community level, by supplying information about management

practices, productivity and seasonal vegetation dynamics (Weber et al. 2018). Remote sensing in combination with Geographic Information Systems (GIS) can be very cost-effective techniques, allowing the measurement of landscape-level temporal changes over a continuous area (Gillespie et al. 2018). Thus, the analysis of spectral reflectance provides an inexpensive, non-invasive and fast method for assessing the degree of damage in vegetation affected by environmental stresses (Davids and Tyler 2003).

Through the use of multi-spectral satellite images, the characterization of vegetation is made possible by its reflectance properties (Weber et al. 2018). This is achieved using the Normalized Difference Vegetation Index (NDVI) introduced by (Tucker 1979), being widely applied in research on global climate and environmental change (Gandhi et al. 2015; Rao et al. 2015; Fan and Liu 2016; Brehaut and Danby 2018; Chasmer et al. 2018; Gillespie et al. 2018; Kern et al. 2018; Weber et al. 2018; Zhang et al. 2018). NDVI represents the photosynthetic activity of vegetation and is associated with primary production, biomass, carbon sequestration, plant water stress and biodiversity (Gillespie et al. 2018). However, the link to metrics like plant growth and species abundance is less clear (Brehaut and Danby 2018). The NDVI is determined by the normalized difference between the reflectance in the near infrared (*NIR*) and the visible red (*Red*) spectral bands by the following Equation (1):

$$(1) \quad NDVI = \frac{(NIR - Red)}{(NIR + Red)}$$

The study by (Davids and Tyler 2003) has demonstrated that remote sensing has the potential to provide a monitoring technique to assess the ecological impact of radionuclide contamination and how the NDVI and other vegetation indexes can measure the effect of radionuclide contamination and soil moisture on the vegetation. It also shows that silver birch (*Betula pendula*) and Scots pine (*Pinus sylvestris*) trees have different responses to radionuclide contamination.

1.10 Objectives:

Understanding ecological effects of radioactive contamination offers benefits for environmental preparedness and management, remediation actions, and puts radiation effects into context with other factors affecting the biota (Bréchignac et al. 2016). Moreover, the study of natural populations in their ecological settings is fundamental to investigate the consequences of radiological contamination (Bréchignac et al. 2016).

Responses of organisms through time to the chronic radiation exposure in their natural environment caused by the Chernobyl accident are not yet clear. Various studies found that plant growth rate and seed germination have been negatively affected by radiation (Mousseau et al. 2013; Mousseau et al. 2014; Boratyski et al. 2016), while others reported increased mammal abundances (Deryabina et al. 2015), no effects on the relative abundance of fish (Lerebours et al. 2018) and natural forest succession (Laćan et al. 2015), with the latter benefitting from the human absence since the accident. It seems that even under hazardous ionizing radiation exposure that affects organisms at the individual level (reduced fitness and/or growth), those effects are not enough to restrain populations' abundance. Field studies may deliver less certainty about causes and effects, but they benefit from higher ecological relevance when compared with laboratory experiments (Bréchnac et al. 2016). Thus, it became an interest to analyse: (1) how the vegetation primary production changed after the accident and (2) how those changes relate to radiation exposure.

For that purpose, the main objectives of this work were to: (1) analyse the NDVI changes inside the CEZ from before, during and after the Chernobyl nuclear accident; and (2) determine whether the main cause for the NDVI changes (if they exist) is due to the radiation exposure and/or due to the alteration in land use caused by the land abandonment.

The following hypothesis were tested: (1) the vegetation suffered a negative change in NDVI values following the Chernobyl accident, while recovering those NDVI values over the years; (2) The NDVI has a negative linear relationship with radiation; (3) Different classes of vegetation have different responses to radiation exposure.

2. Materials & Methods

Free satellite images from the Landsat series (4, 5, 7 and 8) were downloaded from the EarthExplorer website from the United States Geographical Survey (USGS) and also from the European Space Agency (ESA) website, that included the entirety of the Chernobyl Exclusion Zone (path=182, row=24). The Landsat satellite sensors have an optimal spatial resolution (30 meters resolution at the visible and near infrared bands), allowing for the successful capture of spatial details (Rao et al. 2015). The downside however is the long observation cycle (16 days) and the frequent cloud contamination that limit their application and imagery utility.

Using different orbit scenes and complementing them together was impractical because of the different date between them, as they would be from different seasons and/or different vegetation stages, leading to different NDVI values. As a requirement, these images needed

to be clouds free above the target area, as well as snow free, to facilitate the image processing tasks.

First, only the EarthExplorer search engine was used, but because not many images satisfied the requirements, the USGS support team was contacted, while also evidencing the fact that they did not have any images for some years. They responded that although they have established the Landsat Global Archive Consolidation (LGAC) in 2010 (Wulder et al. 2016), which is an effort to collect data from worldwide stations, some areas of interest were affected by the commercialization of the Landsat Thematic Mapper (TM) data in the 1980's and 1990's and were not collected. As they advised to contact other International Ground Stations (IGS), the ESA was contacted to get access to their imagery collection, as they would might have some unique products not present in the USGS archives. Thus, the ESA datasets were accessed and more images were obtained.

Regarding the USGS images, they belong to the Landsat Collection 1 Level-1 dataset, which is processed with the Landsat Product Generation System (LPGS). The ESA images are from the high-quality ortho-rectified L1T datasets.

The selected images were then processed in QGIS (v2.18.17), with the Semi-Automatic Classification Plugin (SCP - v5.3.11) (Congedo, L. 2016). The standard Coordinate Reference System (CRS) of the images was used throughout the entire work, designated WGS 84 / UTM zone 35N (EPSG:32635). Using the SCP plugin pre-processing tool for Landsat images, the image bands were chosen and then stacked, after being converted to Top of Atmosphere (TOA) reflectance and where Dark Object Subtraction (DOS1) (Chavez 1988) atmospheric correction was also applied in order to obtain surface reflectance (Song et al. 2001; Congedo, L. 2016).

For the various Landsat satellites used, different bands were selected, as demonstrated by Table 1:

Table 1- Landsat satellites and respective bands selected for use.

Landsat 4-5 Thematic Mapper (TM) & Landsat 7 Enhanced Thematic Mapper Plus (ETM+)	Bands
	Band 3 – Red
	Band 4 – Near Infrared (NIR)

Landsat 8	Bands
	Band 4 – Red
	Band 5 – Near Infrared (NIR)

The stacks were then cropped using a polygon shapefile (Figure 9), which area contained the entirety of the CEZ, plus some area around its border (similar to a buffer, Figure 10), should the need to compare both areas arise. This reduces the stack size and makes posterior image analysis faster. The 30 km CEZ border line was downloaded as a KML file from Google Maps.

Figure 9 - The polygon (in brown) for cropping the target area from the satellite images. The CEZ border appears in red and the sample locations are the little points in black inside the CEZ.

Figure 10 - The cropped target area from a satellite image with the CEZ border in red.

2.1 Field work

Field work was necessary to obtain sample data to be used on the NDVI analysis. This data was gathered by Dr. Neftalí Sillero, Dr. Zbyszek Boratyński and Dr. Igor Chizhevsky. The field trip lasted for 11 days in October 2017 and more than 300 sample points of vegetation locations were registered (Figure 11) using a Trimble GeoExplorer GPS device. These varied from points to lines to polygons features as to be used on QGIS. The trip was accompanied by a tour guide and as it was unsafe to venture further from the usually used roads, all training points were taken near the road and where homogeneous vegetation patches were sighted. A photograph of each registered location was taken to later confirm the vegetation composition of each patch. Using a hand-held dosimeter (Inspector, SE International, Inc, Summertown, TN, USA), the biological radiation dose of each local was also measured (in $\mu\text{Sv}/\text{hour}$), with one entry measure for point features, two entry measures for line features and one point per polygon corner entry measure for polygon features. Some retrieved features had topology errors and were corrected accordingly while others needed to be discarded because of input errors or missing information.

Figure 11 – Close-up of 3 sampled locations (yellow) inside the CEZ and a nearby road (blue).

After adding buffers to the lines (1m to 5m buffer) and points (20m buffer) features, all features were merged into a single shapefile (which would contain buffers of the newly added lines and points plus the polygons features retrieved in the field). The features names described the vegetation class of each patch, even for cases where the patch contained several vegetation types. As this would complicate analysis, the number of different classes was rearranged as given in Table 2:

Table 2 - List of vegetation classes analysed and their samples (features) number.

Number of features	Vegetation class	Description
9	<i>Acacia</i>	Homogeneous patch of <i>Acacia</i>
1	<i>Acer</i>	Homogeneous patch of <i>Acer</i>

Number of features	Vegetation class	Description
12	<i>Alnus</i>	Homogeneous patch of <i>Alnus</i>
11	<i>Alnus</i> mix	Heterogeneous patch where <i>Alnus</i> is dominant
14	<i>Betula</i>	Homogeneous patch of <i>Betula</i>
41	<i>Betula</i> mix	Heterogeneous patch where <i>Betula</i> is dominant
3	Burnt <i>Pinus</i>	Homogeneous patch of burnt <i>Pinus</i>
1	Bushes	Homogeneous patch of bushes
3	Bushes mix	Heterogeneous patch where bushes are dominant
4	Deciduous mix	Heterogeneous patch of deciduous trees
2	<i>Fagus</i> mix	Heterogeneous patch where <i>Fagus</i> is dominant
1	Field	Patch of agricultural land outside the CEZ for comparison purposes
1	<i>Fraxinus</i>	Homogeneous patch of <i>Fraxinus</i>
38	Grassland	Homogeneous patch of grassland
29	Grassland mix	Heterogeneous patch where grassland is dominant
2	Lichens	Homogeneous patch of lichens
2	Marsh	Homogeneous patch of marsh
5	Meadow	Homogeneous patch of meadow
9	Mixed	Heterogeneous patch where there is not any dominant vegetation

Number of features	Vegetation class	Description
63	<i>Pinus</i>	Homogeneous patch of <i>Pinus</i>
34	<i>Pinus</i> mix	Heterogeneous patch where <i>Pinus</i> is dominant
1	<i>Populus</i>	Homogeneous patch of <i>Populus</i>
4	<i>Populus</i> mix	Heterogeneous patch where <i>Populus</i> is dominant
11	<i>Quercus</i>	Homogeneous patch of <i>Quercus</i>
11	<i>Quercus</i> mix	Heterogeneous patch where <i>Quercus</i> is dominant
1	<i>Robinia</i>	Homogeneous patch of <i>Robinia</i>

2.2 Cloud Masking

Due to the lack of available cloud free images, the stacks of Landsat images with some clouds present above the target area were cloud masked using the Cloud Masking plugin ([Bitbucket](#) – v18.2.7) for QGIS that uses the Fmask algorithm, which is the most accurate and widely use algorithm (Zhu and Woodcock 2012). The values for the cloud probability threshold (percentage) of the Fmask algorithm were adjusted to try to obtain an accurate cloud mask for each clouded image. This threshold regulates the commission and omission errors upon the creation of the cloud mask. Therefore, when the default threshold value of 0.225 was inaccurately masking pixels, it needed to be adjusted to better mask the pixels representing clouds. Incompatibility problems arose with the use of ESA Landsat images and so the plugin developer and the ESA were contacted and the problem was reported ([Issue tracker](#)). It appears that the plugin did not support the ESA Landsat products, and so, with the effort of the ESA helpdesk service team, the use of an adapted python source code of the plugin was recommended, and the cloud masks for the ESA images were partly created. This means that the layer of the cloud mask was created but not automatically applied to the image stack. To complete the cloud masking, through manual processing using R software, the cloud mask layer cropped the stacked image and then a reclassification of pixels was performed. This required custom R scripts to be created as to facilitate posterior NDVI measurements on all images.

2.3 Seasonal datasets

The images were divided in 2 datasets based on the date they were taken, the Foliage season dataset and the No-Foliage season dataset (Table 3). Throughout the year, the vegetation productivity changes as the annual seasons pass, changing with them the NDVI values. This difference is even more relevant with the loss of leaves by deciduous trees, making the NDVI pattern of each vegetation class differ from the Foliage and No-Foliage season. Thus, images dating from May 1st to September 15th belong to the Foliage season dataset and images dating from September 16th to April 30th belong to the No-Foliage season dataset. This date range was established after observations at the oscillations of different weather variables (i.e. temperature, cloud cover, precipitation) throughout an entire year in the Kiev area ([weatherspark](#)). It is important to note that the vegetation in images from the No-Foliage season dataset can still have, and in most cases do have leaves, for the period between September 16th until snow starts to fall (and thus rendering the images useless) is very short and not many images were available. Nevertheless, a significant difference in NDVI values is expected when comparing the Foliage and No-Foliage datasets.

Table 3 - Number of obtained satellite images per season dataset and year.

Year	Foliage Dataset	No-Foliage Dataset
1982	0	0
1983	0	0
1984	0	1
1985	1	1
1986	1	0
1987	2	1
1988	1	0
1989	1	2
1990	1	1
1991	1	0
1992	3	1
1993	1	0
1994	1	1
1995	3	2
1996	1	1
1997	1	1
1998	0	1
1999	1	2
2000	2	3
2001	2	2
2002	1	1
2003	0	2

Year	Foliage Dataset	No-Foliage Dataset
2004	1	2
2005	1	0
2006	1	1
2007	0	1
2008	0	1
2009	1	1
2010	1	1
2011	1	1
2012	0	0
2013	0	1
2014	1	5
2015	0	0
2016	1	0
2017	1	1
TOTAL	33	38

Using ENVI (v5.3) software, the NDVI profile of each image was created from the images stacks (images with no clouds) or from the cloud masked stacks (images that originally had clouds). The NDVI values were then extracted using R software. Using the field retrieved sample locations, the arithmetic mean of the NDVI values for each feature was estimated. The NDVI values along the years were then analysed, for different classes of vegetation and different levels of radiation as well as its variation.

Different groups of years were created, each representing a different stage (Table 4): Group 1 are images from the years before the accident; Group 2 are images from the day of the accident (April 26th, 1986) to the completion of the construction of the sarcophagus (December, 1986); Group 3 are images from December 1986 until 1990 (completion of clean-up operations); and Group 4 are images from 1990 to 2017. It is important to note that due to a shortage of acceptable images, Group 1 and Group 2 of the Foliage season dataset contain only 1 image each, and that there are no images from the No-Foliage season dataset in Group 2.

Table 4 - Distribution of years through different groups.

Group 1	Group 2	Group 3	Group 4
1984 – 1986 (before accident)	1986 (accident) – 1986 (sarcophagus)	1986 (sarcophagus) – 1990	1990 – 2017

2.4 Hypothesis Testing

1. How did NDVI change following the accident?

To test if primary production (measured by the NDVI) was affected by the Chernobyl's accident radioactive releases, Analysis of Variance (ANOVA) and Kruskal-Wallis tests were conducted using R software to analyse the NDVI variance between the period before and after the accident. More specifically, the NDVI variance between the four different groups (Table 4) of years established (ANOVA model: NDVI~Group; Group as a factor). A pairwise t-test was also performed to analyse the variance between different pairs of groups of years, where the p-values were adjusted by the Benjamini-Hochberg (BH) method. This method decreases the false discovery rate, which means that it helps to avoid Type I errors (false positives). To determine which type of test (ANOVA or Kruskal-Wallis) was to be conducted for each vegetation class, the homoscedasticity of the data was checked using the Bartlett's test, while also performing a logarithmic transformation of the data when needed. Therefore, the Kruskal-Wallis test was performed on classes in which the Bartlett's test still returned a heteroscedastic result (p-value < 0.05) even after a logarithmic transformation of the data.

2. Does NDVI have a negative linear relationship with radiation?

To investigate how the NDVI currently relates to radiation, a linear model and a Generalized Additive Model (GAM) test were performed using R software. The GAM test used the "mgcv" and the "ggplot2" R packages. The image used for the retrieval of these NDVI values dates 1 month prior to the retrieval of the radiation measurements during field work, as it was the closest image taken to that timeframe. This image had some clouds present above the target area, so the cloud masking was applied. Therefore, features with null NDVI values caused by the overlapping of features with cloud masked areas were discarded. Furthermore, only classes with a number of features equal or superior than 10 were taken into account, so they can be statistically significant for the tests.

3. Different classes of vegetation responded differently to radiation?

The tests described above were automatically performed on every different class of vegetation, to determine if there are differences between the vegetation classes.

3. Results

3.1 NDVI variance between groups

Depending on the result of the Bartlett's test, different classes of vegetation underwent different types of analysis (Table 5 for the Foliage dataset; Table 6 for the No-Foliage

dataset). Some classes were excluded because there were not sufficient data (less than 2 features on any group) to perform the analysis (6 classes excluded on the Foliage dataset and 2 classes from the No-Foliage dataset). The boxplots presented in Figure 12 and Figure 13 depict the variance between all the NDVI values for all vegetation classes of each season dataset and the different groups of years. The boxplots for each individual vegetation class are present at the end of this document in Appendix I and Appendix II.

Table 5 – ANOVA and Kruskal-Wallis test results for all vegetation classes of the Foliage season dataset to assess the NDVI variance between groups of years. “N” represents the number of features analysed for each class of vegetation; “F” represents the F-value of the ANOVA test; “ χ^2 ” represents the χ^2 value of the Kruskal-Wallis test; “Df” represents the degrees of freedom; The “All” class represents the result of the test taking into account all vegetation classes together.

Classes	Test	N	F / χ^2	Df	p-value
All	Kruskal-Wallis	10269	261.27	3	<0.001 ***
Acacia	Kruskal-Wallis	297	4.978	3	0.173
Alnus	ANOVA	387	10.97	1	0.001 **
Alnus mix	Kruskal-Wallis	358	26.078	3	<0.001 ***
Betula	ANOVA	459	26.68	1	<0.001 ***
Betula mix	ANOVA	1348	66.93	1	<0.001 ***
Burnt Pinus	ANOVA	99	1.978	1	0.163
Bushes mix	ANOVA	98	0.468	1	0.496
Deciduous mix	Kruskal-Wallis	132	8.975	3	0.030 *
Fagus mix	Kruskal-Wallis	66	10.163	3	0.017 *
Grassland	Kruskal-Wallis	1251	51.842	3	<0.001 ***
Grassland mix	ANOVA	955	0.354	1	0.552
Lichens	ANOVA	66	0.545	1	0.463
Marsh	Kruskal-Wallis	66	5.273	3	0.153
Meadow	ANOVA	164	0	1	0.986
Mixed	ANOVA	296	13.94	1	<0.001 ***
Pinus	Kruskal-Wallis	2061	100.1	3	<0.001 ***
Pinus mix	ANOVA	1118	1.928	1	0.165
Populus mix	ANOVA	132	5.508	1	0.020 *
Quercus	Kruskal-Wallis	359	19.065	3	<0.001 ***
Quercus mix	Kruskal-Wallis	359	21.31	3	<0.001 ***

Signif. codes: 0 '****' 0.001 '***' 0.01 '**' 0.05

Figure 12 - Boxplot taking all classes of vegetation together for the Foliage dataset, showing the differences of NDVI values between groups of years (NDVI~Group). Group 1 (1984-1986); Group 2 (1986-1986); Group 3 (1986-1990); Group 4 (1990-2017).

Table 6 – ANOVA and Kruskal-Wallis test results for all vegetation classes of the No-Foliage season dataset to assess the NDVI variance between groups of years. “N” represents the number of features analysed for each class of vegetation; “F” represents the F-value of the ANOVA test; “ χ^2 ” represents the χ^2 value of the Kruskal-Wallis test; “Df” represents the degrees of freedom; The “All” class represents the result of the test taking into account all vegetation classes together.

Classes	Test	N	F / χ^2	Df	p-value
All	Kruskal-Wallis	11799	32.596	2	<0.001 ***
Acacia	Kruskal-Wallis	341	0.814	2	0.666
Acer	Kruskal-Wallis	38	0.39	1	0.536
Alnus	Kruskal-Wallis	453	6.851	2	0.032 *
Alnus mix	Kruskal-Wallis	410	1.381	2	0.501
Betula	Kruskal-Wallis	528	4.186	2	0.123
Betula mix	Kruskal-Wallis	1541	12.746	2	0.002 **
Burnt Pinus	ANOVA	112	1.895	1	0.171
Bushes	ANOVA	38	0.472	1	0.496
Bushes mix	Kruskal-Wallis	114	1.4	2	0.497
Deciduous mix	Kruskal-Wallis	152	2.036	2	0.361
Fagus mix	ANOVA	72	0.017	1	0.898
Field	ANOVA	38	0.478	1	0.494

Classes	Test	N	F / χ^2	Df	p-value
Grassland	Kruskal-Wallis	1438	29.383	2	<0.001 ***
Grassland mix	Kruskal-Wallis	1098	17.819	2	<0.001 ***
Lichens	ANOVA	75	3.3	1	0.073
Marsh	Kruskal-Wallis	76	2.187	2	0.335
Meadow	Kruskal-Wallis	190	0.091	2	0.956
Mixed	Kruskal-Wallis	340	10.368	2	0.006 **
Pinus	Kruskal-Wallis	2375	38.469	2	<0.001 ***
Pinus mix	Kruskal-Wallis	1278	2.684	2	0.261
Populus mix	Kruskal-Wallis	152	2.672	2	0.263
Quercus	Kruskal-Wallis	413	2.381	2	0.304
Quercus mix	Kruskal-Wallis	415	3.789	2	0.150
Robinia	ANOVA	38	0.054	1	0.818

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05

Figure 13 - Boxplot taking all classes of vegetation together for the No-Foliage dataset showing the differences of NDVI values between groups of years (NDVI~Group). Group 1 (1984-1986); Group 3 (1986-1990); Group 4 (1990-2017).

A pairwise t-test was performed to calculate pairwise differences between groups for each vegetation class of each season dataset (Table 7 and Table 8). The p-values were adjusted by the Benjamini-Hochberg (BH) method. The t-test returned significant values (p-value < 0.05) when the different vegetation classes were not considered, and were independent of

the season dataset. For the Foliage season dataset, the majority of significant changes were observed between Groups 1-2, Groups 1-3 and Groups 1-4 (“*Alnus*”, “*Betula* mix”, “*Pinus* mix”, “*Quercus*” and “*Quercus* mix” classes), but it was observed that some classes of vegetation (“*Acacia*”, “*Burnt Pinus*”, “*Bushes* mix”, “*Deciduous* mix”, “*Fagus* mix”, “*Lichens*”, “*Marsh*”, and “*Meadow*” classes) did not suffer any significant change between the different groups of years. For the No-Foliage season dataset, the majority of the vegetation classes did not show a significant change between any of the groups of years, except for the “*Betula* mix”, “*Grassland*”, “*Grassland* mix”, “*Mixed*”, and “*Pinus*” classes, even though the t-test result when not accounting for the vegetation classes returned a significant p-value between all groups of years.

Table 7 - p-values of the pairwise t-test for all classes of vegetation of the Foliage season dataset. “N” represents the number of features analysed for each class of vegetation.

Classes	N	Groups 1-2	Groups 1-3	Groups 1-4	Groups 2-3	Groups 2-4	Groups 3-4
All	10071	<0.001 ***	<0.001 ***	<0.001 ***	<0.001 ***	0.293	<0.001 ***
<i>Acacia</i>	297	0.50	0.24	0.25	0.48	0.50	0.48
<i>Alnus</i>	387	<0.01 **	<0.001 ***	<0.001 ***	0.832	0.832	0.832
<i>Alnus</i> mix	358	<0.01 **	<0.001 ***	<0.01 **	0.932	0.224	<0.01 **
<i>Betula</i>	459	0.015 *	0.010 *	<0.001 ***	0.599	0.371	<0.01 **
<i>Betula</i> mix	1348	<0.001 ***	<0.001 ***	<0.001 ***	0.212	0.079	0.311
<i>Burnt Pinus</i>	99	0.73	0.73	0.73	0.73	0.73	0.73
<i>Bushes</i> mix	98	0.57	0.42	0.42	0.81	0.98	0.57
<i>Deciduous</i> mix	132	0.11	0.11	0.11	0.82	0.82	0.82
<i>Fagus</i> mix	66	0.12	0.12	0.23	0.78	0.27	0.12

Classes	N	Groups 1-2	Groups 1-3	Groups 1-4	Groups 2-3	Groups 2-4	Groups 3-4
Grassland	1251	<0.001 ***	<0.001 ***	<0.001 ***	<0.01 **	0.486	<0.001 ***
Grassland mix	955	<0.001 ***	<0.001 ***	<0.001 ***	0.459	0.096	<0.001 ***
Lichens	66	0.80	0.80	0.80	0.80	0.80	0.91
Marsh	66	0.70	0.70	0.87	0.87	0.70	0.37
Meadow	164	0.51	0.16	0.50	0.51	0.97	0.16
Mixed	296	0.127	<0.001 ***	<0.001 ***	0.127	0.127	0.910
<i>Pinus</i>	2061	<0.001 ***	<0.001 ***	<0.001 ***	<0.01 **	0.042 *	<0.01 **
<i>Pinus</i> mix	1118	0.049 *	<0.01 **	<0.01 **	0.632	0.922	0.157
<i>Populus</i> mix	132	0.236	0.025 *	0.025 *	0.620	0.620	0.998
<i>Quercus</i>	359	<0.01 **	<0.001 ***	<0.001 ***	0.607	0.867	0.102
<i>Quercus</i> mix	359	<0.01 **	<0.001 ***	<0.001 ***	0.879	0.508	0.070

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05

Table 8 - p-values of the pairwise t-test for all classes of the No-Foliage season. "N" represents the number of features analysed for each class of vegetation.

Classes	N	Groups 1-3	Groups 1-4	Groups 3-4
All	11725	<0.01 **	<0.001 ***	<0.01 **
<i>Acacia</i>	314	0.69	0.69	0.93
<i>Acer</i>	38	0.93	0.93	0.93
<i>Alnus</i>	453	0.351	0.061	0.142

Classes	N	Groups 1-3	Groups 1-4	Groups 3-4
<i>Alnus mix</i>	410	0.78	0.87	0.62
<i>Betula</i>	528	0.94	0.24	0.22
<i>Betula mix</i>	1541	0.192	<0.01 **	0.040 *
<i>Burnt Pinus</i>	112	0.9	0.44	0.44
Bushes	38	0.83	0.83	0.83
Bushes mix	114	0.53	0.53	0.75
Deciduous mix	152	0.49	0.84	0.49
<i>Fagus mix</i>	72	0.75	0.75	0.75
Field	38	0.75	0.83	0.5
Grassland	1438	<0.001 ***	0.175	<0.001 ***
Grassland mix	1098	0.151	0.619	<0.01 **
Lichens	75	0.22	0.18	0.82
Marsh	76	0.72	0.69	0.69
Meadow	190	0.93	0.93	0.93
Mixed	340	0.092	<0.01 **	0.286
<i>Pinus</i>	2375	<0.01 **	<0.001 ***	<0.001 ***
<i>Pinus mix</i>	1278	0.79	0.48	0.22
<i>Populus mix</i>	152	0.74	0.36	0.36
<i>Quercus</i>	413	0.97	0.22	0.19
<i>Quercus mix</i>	415	0.68	0.47	0.14
<i>Robinia</i>	38	0.83	0.83	0.83

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05

Descriptive NDVI statistics table for groups of years in each season dataset (Foliage / No-Foliage) are present in Table 9 and Table 10:

Table 9 – Descriptive NDVI statistics of each group of the Foliage season (vars=1). “N” represents the number of features; “SD” represents the standard deviation; “Trimmed” represents the mean after the removal of a small percentage of outliers; “Skew” represents the asymmetry of the curve; “Kurtosis” represents the tailedness of the distribution; “SE” represents the standard error.

Group	N	Mean	SD	Median	Trimmed	Mad	Min	Max	Range	Skew	Kurtosis	SE
1	313	0.5	0.13	0.5	0.51	0.12	0.19	0.74	0.55	-0.48	-0.23	0.01
2	312	0.61	0.14	0.62	0.62	0.14	0.26	0.87	0.6	-0.29	-0.51	0.01
3	1562	0.64	0.13	0.65	0.65	0.13	0.16	0.9	0.73	-0.6	0.2	0
4	8082	0.62	0.14	0.64	0.63	0.14	0.1	0.9	0.8	-0.53	-0.2	0

Table 10 – Descriptive NDVI statistics of each group of the No-Foliage season (vars=1). “N” represents the number of features; “SD” represents the standard deviation; “Trimmed” represents the mean after the removal of a small percentage of outliers; “Skew” represents the asymmetry of the curve; “Kurtosis” represents the tailedness of the distribution; “SE” represents the standard error.

Group	N	Mean	SD	Median	Trimmed	Mad	Min	Max	Range	Skew	Kurtosis	SE
1	611	0.42	0.11	0.42	0.42	0.12	0.21	0.73	0.52	0.34	-0.62	0
3	1203	0.45	0.1	0.44	0.44	0.09	0.19	0.76	0.58	0.68	0.83	0
4	9985	0.46	0.15	0.45	0.45	0.17	0.02	0.88	0.86	0.35	-0.58	0

3.2 NDVI and radiation relationship

The result of the linear model taking all the values from every vegetation class feature showed that there is not a significant relationship ($F(1,307)=3.774$, $p=0.053$) between the two variables (NDVI and radiation) and the same was observed with the logarithmic transformed data ($F(1,307)=2.229$, $p=0.130$). The relationship is also non-linear by looking at the plots with untransformed and transformed (log) data (Figure 14 and Figure 15 respectively). Following this, a generalized additive model (GAM) was performed, also taking into account the different classes of vegetation (GAM model: $NDVI \sim Radiation$). The results of the GAM are present in Table 11. All vegetation classes returned a non-significant

relationship ($p\text{-value} > 0.05$) expect for the “*Betula*” and “*Betula mix*” classes. Also, only the “*Betula*” class relationship is well explained by this GAM model (69.7%). The “*Betula*” class has an outlier with a high radiation value (200 $\mu\text{Sv/h}$), so to check if the relation was in fact being caused by this outlier, the model was run again without accounting for the outlier. This time, the model returned a $p\text{-value}$ of 0.436, where only 6.17% of the variance was explained.

Figure 14 - Linear model plot for all classes with untransformed data (LM model: NDVI~Radiation).

Figure 15 - Linear model plot for all classes after a logarithmic transformation of the data (LM model: $\log(\text{NDVI}) \sim \log(\text{Radiation})$).

Table 11 - Results of the GAM test to assess the relationship between NDVI as function of radiation. "N" represents the number of features analysed for each class of vegetation; "Adjusted r^2 " represents the proportion of deviance explained; "Deviance explained" represents how well the data fits the current model (proportion of the null deviance explained by the model); "GCV score" represents the minimized generalized cross-validation. Family: gaussian; Link function: identity.

Classes	N	Adjusted r^2	Deviance explained (%)	GCV score	t-value	p-value
All	309	0.009	1.21	0.010	-1.943	0.053
<i>Alnus</i>	11	-0.010	9.09	<0.001	0.949	0.368
<i>Alnus mix</i>	11	-0.075	3.27	<0.001	0.552	0.594
<i>Betula</i>	13	0.669	69.7	0.001	-5.025	<0.001***
<i>Betula mix</i>	41	0.156	17.7	0.003	-2.895	0.006**
Grassland	38	-0.004	2.27	0.007	0.915	0.366
Grassland mix	29	0.061	9.44	0.005	1.678	0.105
<i>Pinus</i>	62	0.039	5.46	0.003	1.862	0.068
<i>Pinus mix</i>	33	-0.0309	0.135	0.019	-0.205	0.839
<i>Quercus</i>	11	-0.046	5.86	0.001	0.749	0.473
<i>Quercus mix</i>	11	-0.107	0.403	0.002	0.191	0.853

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05

Descriptive statistics table of radiation values ($\mu\text{Sv/hour}$) per class of vegetation are present in Table 12:

Table 12 - Statistics of radiation values for each class of vegetation (vars=1). "N" represents the number of features; "SD" represents the standard deviation; "Trimmed" represents the mean after the removal of a small percentage of outliers; "Skew" represents the asymmetry of the curve; "Kurtosis" represents the tailedness of the distribution; "SE" represents the standard error.

Classes	N	Mean	SD	Median	Trimmed	Min	Max	Range	Skew	Kurtosis	SE
<i>Acacia</i>	9	1.039	1.049	0.591	1.039	0.234	2.876	2.642	0.906	-1.039	0.350
<i>Acer</i>	1	0.165	NA	0.165	0.165	0.165	0.165	0	NA	NA	NA

Classes	N	Mean	SD	Median	Trimmed	Min	Max	Range	Skew	Kurtosis	SE
<i>Alnus</i>	11	1.133	2.173	0.265	0.546	0.14 4	7.411	7.267	2.155	3.356	0.655
<i>Alnus</i> mix	11	0.473	0.517	0.243	0.356	0.10 0	1.892	1.792	1.785	2.229	0.156
<i>Betula</i>	13	23.27 4	54.87 9	2.997	9.281	0.12 9	200.3 50	200.22 1	2.543	5.358	15.22 1
<i>Betula</i> mix	41	4.782	7.320	0.824	3.248	0.13 3	25.36 3	25.230	1.518	0.908	1.143
<i>Burnt</i> <i>Pinus</i>	3	5.935	8.180	2.222	5.935	0.27 0	15.31 3	15.043	0.360	-2.333	4.723
Bushes	1	4.018	NA	4.018	4.018	4.01 8	4.018	0	NA	NA	NA
Bushes mix	3	7.041	6.868	7.016	7.041	0.18 6	13.92 3	13.737	0.004	-2.333	3.965
Deciduou s mix	4	0.464	0.136	0.462	0.464	0.32 6	0.606	0.280	0.011	-2.341	0.068
<i>Fagus</i> mix	2	0.181	0.022	0.181	0.181	0.16 6	0.196	0.031	0	-2.750	0.015
Field	1	0.211	NA	0.211	0.211	0.21 1	0.211	0	NA	NA	NA
<i>Fraxinus</i>	1	1.319	NA	1.319	1.319	1.31 9	1.319	0	NA	NA	NA
Grasslan d	38	1.556	3.101	0.619	0.948	0.19 0	18.76 0	18.570	4.536	22.024	0.503
Grasslan d mix	29	1.329	1.383	0.806	1.121	0.16 2	5.508	5.345	1.539	1.634	0.257

Classes	N	Mean	SD	Median	Trimmed	Min	Max	Range	Skew	Kurtosis	SE
Lichens	2	46.36 8	44.73 5	46.368	46.368	14.7 35	78.00 0	63.265	0	-2.750	31.63 3
Marsh	2	1.085	1.360	1.085	1.085	0.12 3	2.047	1.924	0	-2.750	0.962
Meadow	5	4.891	10.32 4	0.258	4.891	0.22 3	23.36 0	23.137	1.073	-0.920	4.617
Mixed	9	4.303	9.385	0.465	4.303	0.23 1	28.64 0	28.410	1.886	2.049	3.128
<i>Pinus</i>	62	3.832	6.364	0.693	2.296	0.12 9	27.75 0	27.621	2.110	3.739	0.808
<i>Pinus</i> mix	33	3.499	6.578	0.386	1.929	0.10 8	27.47 0	27.362	2.251	4.463	1.145
<i>Populus</i>	1	0.219	NA	0.219	0.219	0.21 9	0.219	0	NA	NA	NA
<i>Populus</i> mix	4	0.348	0.276	0.289	0.348	0.10 8	0.709	0.601	0.312	-2.075	0.138
<i>Quercus</i>	11	9.686	12.49 3	2.997	8.326	0.15 1	31.46 0	31.309	0.839	-1.146	3.767
<i>Quercus</i> mix	11	2.813	4.853	0.364	1.65	0.21 1	15.88 5	15.674	1.760	1.900	1.463
<i>Robinia</i>	1	0.862	NA	0.862	0.862	0.86 2	0.862	0	NA	NA	NA

The GAM plots produced for each individual class of vegetation are present at the Appendix III at the end of this document.

4. Discussion

4.1 NDVI variance between groups

When analysing each individual vegetation class, some classes clearly expressed significant changes by an increase of the NDVI values over time while other classes did not. Overall, the difference between the NDVI values of different groups (especially Groups 1-2, 1-3 and 1-4) suggest that the NDVI values suffered a significant positive change (increase of NDVI values) after the Chernobyl accident. Surprisingly, this change also turned out to be positive between Group 1 (1984-1986) and Group 2 (1986-1986, image after the accident) by analysing the boxplots of Figure 12 and Figure 13 and the boxplots for each vegetation class present in the Appendix I for the Foliage season dataset. It is important to note that although the images from those groups are in the same assigned Foliage season dataset, they are from different months (the image from Group 1 is from September 1st 1985 and the image from Group 2 is from May 31st 1986). Therefore, caution is advised when interpreting the results from these two groups, because the difference in NDVI values could be due to different vegetation stages for they are from different annual seasons (early autumn and late spring respectively). Different years could have different timeframes for each ecological season (i.e. different phenology, as a possible result of climate change) meaning, for example, that the deciduous vegetation could start losing leaves at different times (Gallinat et al. 2015), affecting the NDVI values range for images within the same attributed season (Foliage or No-Foliage datasets). The misplacement of the satellite images on the attributed season datasets could introduce errors that reduce the reliability of the data analysis. Recently, a free and open source tool for the analysis of vegetation index time-series from satellite images, namely QPhenoMetrics, was developed for QGIS (Duarte et al. 2018). This tool allows for the computation of phenology metrics, such as: (1) Start of Season Time (SOST, beginning of measurable photosynthesis in the vegetation canopy); (2) Start of Season NDVI (SOSN, Level of photosynthetic activity at the beginning of measurable photosynthesis); (3) End of Season time (EOST, End of measurable photosynthesis in the vegetation canopy); (4) End of Season NDVI (EOSN, Level of photosynthetic activity at the end of measurable photosynthesis); (5) Time of Maximum (MAXT, Time of maximum photosynthesis in the canopy); (6) Maximum NDVI (Maximum level of photosynthetic activity in the canopy); (7) Duration (Length of photosynthetic activity (the growing season)); (8) Amplitude (Maximum increase in canopy photosynthetic activity above the baseline) ([USGS, Sep 2018](#)). The use of such a tool could help decide onto what season dataset the obtained satellite images should be placed at. However, those phenology determinations must be conducted separately on each type of vegetation class, as different species will have

different phenology metrics values. As this method also requires a high number of available and usable satellite images per year, it would be difficult to apply it in situations where few images are available, like in this current study.

Regarding Groups 1-2, 1-3 and 1-4, the results may suggest that the positive impacts on the vegetation caused by the abandonment of the land were superior to the negative impacts of radiation, given the significant increase of NDVI values. It is also possible that the negative effect of radioactive contamination on herbivores abundance (e.g. insects) (Møller and Mousseau 2009) resulted in an increase of primary production because of lowered predation on the vegetation, irrespective from contamination. In 2001, the prognosis for the next ten years (2001-2011) elaborated by (Committee 2001), referred that the area inside the CEZ covered by coniferous and deciduous forest would increase to 65-70% of the whole zone, and that the fauna would stabilize regarding the numbers of forest animal species, with an increase in the number of predators given the absence of hunting and poaching of mammal species. The results of the current study seem to be in line with that prognosis, at least with primary production demonstrating an increase through NDVI values over the years since the accident. It was also reported by (International Atomic Energy Agency 2008), that as early as 1987, recovery processes were evident in the surviving tree canopies. The (International Atomic Energy Agency 2008) report also points out the fact that the recovery of affected biota inside the CEZ has been confounded by the overriding response to the removal of human activities like agriculture, hunting, and fishing, which resulted in the expansion of the populations of plants and animals. This leads to the conclusion that the present environmental conditions have had a positive impact on the biota inside the CEZ (International Atomic Energy Agency 2008).

The No-Foliage season dataset did not show changes on the same level as the changes observed on the Foliage season dataset, what is to be expected as some vegetation classes lose leaves which will affect the NDVI values negatively. Analysing the pairwise comparisons, some vegetation classes like "*Acacia*" did not show a significant change in the NDVI values between any of the pairs of years and not even for the two different season datasets. It is unknown if this is due to: (1) very low radiation values on areas where *Acacia* is present that do not significantly impact its primary production; if (2) *Acacia* is somewhat resistant or adapts well to this radiation stress, or (3) another unaccounted effect is masking the impact of radiation. Other classes like "*Pinus*" had significant NDVI changes between all pairs of years and for the two season datasets. *Pinus* are evergreen trees so because they do not lose leaves, the significant NDVI variance remains the same regardless of season. The "*Betula*" class on the other hand, showed a significant change between groups of years on the Foliage season dataset, but did not show that significant change on the No-Foliage

season dataset. This makes sense since *Betula* trees are deciduous and will lose leaves in the No-Foliage season regardless if they are healthy or not. The “Deciduous mix” class should have had the same behaviour as the “*Betula*” class, so the fact that it did not, may suggest that changes on classes containing a mix of different types of vegetation cannot be so well predicted as homogenous and pure classes of vegetation are.

As an answer to the initial hypothesis made, that the vegetation suffered a negative change in NDVI values following the Chernobyl accident while recovering those NDVI values over the years, the NDVI values increased over the years after the accident, but the apparent increase of NDVI values immediately after the accident is not well understood since there is a lack of sufficient and reliable data.

4.2 NDVI and radiation relationship

All vegetation classes returned no significant values except for the “*Betula*” and “*Betula* mix” classes where the negative effect of radiation on NDVI was evident, and the models explained 69.7% of the relation between the variables for the “*Betula*” class and 17.7% for the “*Betula* mix” class. By looking at the GAM plots (Appendix III), it is observable the presence of outliers, which represent features located near or in the Red Forest area, strongly contributed to this significant relation between the NDVI and radiation for these two vegetation classes. This shows that the Red Forest area is still highly contaminated when compared with other areas, even after the clean-up operations took place. These high radiation levels may have a strong negative effect on the vegetation that is not observed in areas less contaminated. After removing the outlier for the “*Betula*” class, the result was similar to all the other vegetation classes, meaning that with the low radiation values measured, no significant relationship between NDVI and radiation is observable (with 6.17% of the deviance explained now for the “*Betula*” class). The “*Betula*” feature which is the outlier has various young *Betula* trees present on the area which may have grown after the clean-up operations. Still, it is not certain if the low NDVI value measured for that area is due to the effect of radiation or from the fact that the vegetation growing is still young or a combination of both. If these trees started growing right after the clean-up of the area (finished around 1990), they should already be full grown as more than 20 years have passed. The fact that they are not possibly means that they have a reduced growth rate caused by the radiation levels on the area, or that maybe these trees simply started growing a few years ago.

In overall, by analysing the other vegetation classes, it is possible to conclude that the vegetation outside of the Red Forest area is not exposed to radiation levels that can cause a significant impact on primary production. However, this apparent no significant relationship

between NDVI and radiation could be being masked by other variables like soil moisture, vegetation abundance or variation in abundance of herbivores (already mention in the previous section) not accounted in this study. Soil moisture was already identified as being a contributor to vegetation stress and it was measured in the study by (Davids and Tyler 2003), which tried to detect contamination-induced tree stress by soil moisture and radionuclide contamination using various vegetation indexes. As for the vegetation abundance, it may have increased as a result of the abandonment of the land, as mentioned by (International Atomic Energy Agency 2008), masking the negative effects of radiation on the vegetation. A previous study on tree growth rate (Mousseau et al. 2013) demonstrated a highly significant negative effect of background radiation on mean growth rate in the period of 1986-1990. While this shows a clear reduction of individual growth, it is not known whether it significantly impacted the vegetation abundance in a negative way, especially taking into account the land abandonment. For a given pixel, if a comparison of the NDVI value between the pre and post-accident state was made, even though the vegetation before the accident may have been in a normal physiological state, the vegetation cover of that pixel could be inferior to the vegetation cover of the current vegetation state. This increase in vegetation cover as a result of the land abandonment could be responsible for the increased NDVI value returned for that given pixel, despite the current radiological condition. This could mean that various unaccounted variables in conjunction with the positive effect of land abandonment is greater than the negative effect caused by low levels of radiation exposure on the vegetation, but only until a certain radiation threshold level where the radiation impact on the vegetation is just too great, resulting in lowered primary production. Although this threshold was not determined in this study, the studies by (Garnier-Laplace et al. 2010; Garnier-Laplace et al. 2013) and (Geras'kin and Volkova 2014) already tried to investigate the effects of different radiation doses on vegetation and other organisms. The suggested value of 10 $\mu\text{Gy/h}$ was derived in which no effect at the population or ecosystem level is expected (Garnier-Laplace et al. 2010; Geras'kin and Volkova 2014). This value should be carefully analysed because different organisms (animals and plants) have different radiation sensitivities (Woodhead and Zinger 2003), and this happens even with different vegetation species (such as *Pinus sylvestris* and *Betula pendula*) which showed very different responses to radionuclide contamination as reported by (Davids and Tyler 2003). According to the FASSET Radiation Effects Database (FRED) (Woodhead and Zinger 2003), plant growth starts to be affected at $>100 \mu\text{Gy/h}$, and where continued exposure at $12 \mu\text{Gy/h}$ for 8 years increases the sensitivity in pines, with 50% mortality at $\sim 10^3 \mu\text{Gy/h}$ for the same duration. The three most important manifestations of radiation damage in vegetation studies are inhibition of growth, reduction of reproductive capacity (fitness) and death (Woodhead and Zinger 2003). These manifestations are dependent on the radiosensitivity of the plants, which can depend on the

plants' age or development (younger plants, with cells with high proliferation rates are more radiosensitive than mature plants), season (the vegetative state is more radioresistant than the flowering stage), and water content (indirectly increases seed radiosensitivity of tree species by affecting the rate of physiological activity) (Woodhead and Zinger 2003). Also, the ratios of acute to chronic daily dose for exposure that causes a slight slowing of plant growth are ~10 for herbaceous plants and ~60 for arboreal plants (Sparrow 1966; Woodhead and Zinger 2003).

The results of the current study seem to support the results from (Davids and Tyler 2003) where the NDVI values were independent of contamination levels for *Pinus sylvestris* and *Betula pendula* for in situ measurements. Yet, laboratory observations and other vegetation indexes used (e.g, Chlorophyll red edge, Three Channel Vegetation Index) in the same study contradict those in situ measurements. This emphasizes the importance of the use of various vegetation indexes simultaneously and accounting for confounding factors. The effect of clean-up operations may have reduced radiation exposure to a level that the vegetation can tolerate and is still able to strive without major reductions in fitness or plant growth. A possible adaptation through genetic mutations leading to resistance to low levels of radiation exposure could also explain why the vegetation does not seem to be affected by this radiation exposure. The study by (Geras'kin and Volkova 2014) showed that *Pinus sylvestris* has an antioxidant activity sufficiently capable of eliminating different types of ROS produced by chronic radiation exposure in the range of 0.8 to 14.8 $\mu\text{Gy/h}$. The majority of the features used may correspond to areas that were not heavily affected by radiation even right after the accident, since these features were taken within a wide area range inside the CEZ. Areas under heavier radiation exposure could show some relationship between NDVI values and radiation levels. Therefore, more areas in the Red Forest zone should be sampled and analysed, to understand if the NDVI and radiation relationship shows a significant pattern at considerably higher levels of radiation, where it is known that radiation begins to affect plant growth ($>100 \mu\text{Gy/h}$, (Woodhead and Zinger 2003)). The radiation values used are the ones retrieved in 2017 during field work, therefore the measured relationship between NDVI and radiation is only analysing the current state of the vegetation under current radiological conditions. Since many years have passed, the state of the vegetation and relationship between the two variables could have changed. For example, if a certain location had been cleaned up from radioactive contaminants as well as go through a class of vegetation change, that exact same area could now have a different relationship between the variables from what it had before. Although the decay of certain radioactive elements is very long (more than 100 years), the short lived radionuclides which caused the biggest impact (lethal damage) right after the accident (10 to 20 days) are no longer responsible for the current

radiological condition inside the CEZ (Committee 2001). This means that even the vegetation exposed to higher levels of radiation inside the CEZ is not under lethal radiation levels now, but it is expected that that vegetation is sick, possibly showing reduced growth, which effects are expected to be reflected in reduced NDVI values.

Some limitations of the present work that could have also contributed to these results, are: (1) the use of a different number of features per class of vegetation and different size of these same features, within and between classes of vegetation. Even though this can create noise, some variability is needed to perform analyses; (2) some vegetation classes were excluded from the analysis because of their insufficient representability; (3) the NDVI noise originated from the creation of buffers on the points and lines features retrieved from the field; (4) the lack of usable satellite images, especially on the dates close to the year of the accident.

As an answer to the second hypothesis made, that the NDVI has a negative linear relationship with radiation, the NDVI does not have a negative linear relationship with radiation as shown by the results of this study. The reason why this happens was not determined, because other variables that may be responsible for the current vegetation state and NDVI values were not accounted, such as soil moisture, vegetation abundance and abundance of herbivore species, to name a few. A negative relationship between NDVI and radiation was expected due to the known strong negative effects that radiation has on the physiological activity of living beings, such as reduced growth and reduced fitness. It seems that those impacts are very dependent on radiation level, which for lower levels, other variables seem to have a greater impact.

As for the third hypothesis, that different classes of vegetation responded differently to radiation exposure, the NDVI variance tests for groups of years seem to support it, while the NDVI relationship with radiation was practically the same for all vegetation classes. This heavily suggests that other variables like the ones discussed above (human absence, herbivore abundance, soil moisture) rather than radiation levels are influencing the NDVI values and are responsible for the current state of the vegetation inside the CEZ.

5. Conclusion

This work showed that the consequences of the Chernobyl nuclear accident are still not well understood, which is also noted by the existence of studies making contradictory statements. Although current radiation levels can have a negative effect on the vegetation by reducing individual plant growth, similarly to what happens with the reduced fitness of mammals

(Deryabina et al. 2015), these effects do not seem to be enough to hamper vegetation growth at the population level, or that the lower abundance of herbivores compensates the negative effects of radiation.

The NDVI showed to be independent from the radiation values measured. The increase of NDVI values over the years is most likely due to the alteration of land use (land abandonment), the possible reduction of herbivore species caused by radiation exposure and the consequent natural regeneration and ecological succession of the vegetation. This was observed in the abandoned city of Pripjat, demonstrated by (Laćan et al. 2015). The city was overrun by trees and it is now an urban forest as a result of human absence. The results obtained from the current study are also important as they highlight the importance of accounting for confounding factors (e.g. soil moisture) as also suggested previously by (Garnier-Laplace et al. 2013; Bréchnignac et al. 2016). The results show that radiation is not the deterministic factor that rules primary production, at least for the majority of the areas studied which are exposed to lower levels of radiation. It is possible that the human presence in an area has a greater negative impact on the biota than the long term exposure to low levels of ionizing radiation.

It would be interesting to investigate how changes in land cover type, herbivore abundance, clean-up operations, community-level interactions (like facilitation), and natural adaptation to radiation-induced environmental stress could have contributed to the current observable state of the vegetation inside the CEZ. And how these variables are possibly masking the radiation effects on the vegetation.

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Appendix I

Boxplots for each vegetation class of the Foliage season dataset (NDVI~Group):

Appendix II

Boxplots for each vegetation class of the No-Foliage season (NDVI~Group):

Appendix III

Plots of the Generalized Additive Model (GAM) (NDVI~Radiation):