**Machine Learning-Driven Fire risk Assessment for Continuous Cover Forestry in Ireland: A proof of Concept Study**

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**Abstract**

**Forest fires pose significant threats to ecosystem, biodiversity, and human communities, necessitating robust risk assessment strategies to mitigate theory impact. In the context of Continuous Cover Forestry (CCF) forests in Ireland, where sustainable forest management practices are paramount, the development of effective fire risk assessment methodologies is imperative. This study explores the utilization of machine learning techniques for fire risk assessment in CCF Forests, leveraging a combination of meteorological data from the Copernicus Emergency Management Service and simulated forest-specific variables. The dataset obtained from the Copernicus Emergency Management Service provides a comprehensive historical reconstruction of meteorological conditions conducive to fire events, integrated within the European Forest Fire Information System (EFFIS). This dataset encompasses fire danger metrics derived from established models, including the Build-Up Index, Burning Index, Danger Rating, Drought Code, Energy Release Component, and Fine Fuel Moisture Code. Leveraging weather forecasts derived from historical simulations facilitated by the ECMWF ERA5 reanalysis, the dataset offers insights into atmospheric conditions crucial for assessing fire danger levels and formulating pre-suppression plans. In the absence of real-world data specific to CCF forests in Ireland, simulated forest data is utilized to augment the analysis. This simulated dataset comprise essential variables representing various aspects of the forest environment, including overall fire risk, fine fuel moisture, initial spread index, canopy cover, species diversity, drought conditions, wind speed, temperature, fire warnings, and fire occurrence. These variables collectively contribute to a comprehensive understanding of fire risk dynamics within CCF forests, providing a basis for the development of accurate and effective machine learning models. A comparative analysis of various machine learning models including K-nearest Neighbours (KNN), XGBoost, Random Forest, Decision Tree, and support Vector Machines (SVM0, is conducted to assess their performance in fire risk assessment. Rigorous hyperparameter tuning and evaluation through cross- validation are employed to optimise model performance. Results indicate that XGBoost emerges as the most promising model, demonstrating robust performance in handling complex relationships and diverse datasets. This research demonstrates how machine learning supports fire risk assessment for CCF forests in Ireland by integrating meteorological and forest -specific simulate data aiding proactive management for sustainable land use and biodiversity preservation.**

**Keywords:** Continuous Cover Forestry, Data Science, Fire Risk Prediction, Machine Learning, Climate Change, Sustainable Forestry Management.

# **Introduction**

In recent years, Ireland has witnessed a significant increase in the adoption of Continuous Cover Forestry (CCF), with over 53,000 hectares of forests managed under continuous cover systems in 2020 (Coillte Annual Report, 2020). CCF represents a departure from traditional clear-cutting methods, emphasizing the retention of tree cover and a more natural forest structure ( Mason & Kerr, 2001). This approach aligns with Ireland’s commitment to environmental conservation and biodiversity enhancement, aiming to create resilient and ecologically diverse forest ecosystems (Forest Service 200). This research initiative is placed at the intersection of ecological conservation and technological innovation, seeking to asses fire risk assessment in Irish CCF Forests through the application of advanced data science techniques. In this study, a comprehensive dataset from the Copernicus emergency Management Service was utilized, providing a historical reconstruction of meteorological conditions conducive to fire events (Copernicus Emergency Management services). Integrated within the European Forest Fire Information system (EFFIS) this dataset encompasses various fire danger metrics, including the build-Up index, Burning Index, Danger Rating, Drought Code, Energy Release Component, and fine fuel Moisture code (EFFIS). Furthermore, weather forecasts derived from historical simulations facilitated by the ECMWF ERA5 reanalysis were incorporated, offering insights into crucial atmospheric conditions for assessing fire danger levels and formulating pre- suppression plans (ECMWF ERA5). The incorporation of simulated forest data in this study is a strategic response to the absence of real world data specific to CCF in Ireland. This approach aligns with research by ,Calkin, Thompson and Finney(2014), which underscores the necessity of accurate data for effective wildfire management. Their finding advocate for utilising simulated data to complement predictive model when real data is limited. A study by Hong et al. 2004) focuses on the development of a model to simulate forest fuel and fire risk dynamics across landscapes. Their research highlights the importance of accurately representing fuel characteristics and fire behaviour at landscape scales to improve fire risk assessment and inform management strategies. The urgency of this research is underscored by the escalating threat of wildfires globally, as highlighted in a recent report by the United Nations Environment Programme (UNEP) and GRID-Arendal. Titled "Spreading like Wildfire: The Rising Threat of Extraordinary Landscape Fires," the report emphasizes the growing risk of wildfires due to climate change and land-use alterations, projecting a potential surge of up to 50% in extreme fires by the end of the century (UNEP, 2022). These projections emphasize the urgent need for innovative fire risk assessment methods to address evolving environmental challenges.

## **1.1 Research Objectives**

## **1.1.1 Research Problem**

The research problem addressed I this study revolves around the need for robust fire risk assessment methodologies tailored specifically for CCF in Ireland. Despite the recognised environmental benefits of CCF, such as biodiversity conservation and enhanced resilience to climate change, the heterogeneous and dynamic nature of these forests poses challenges for conventional fire risk models designed for uniform, even-ages plantations. The lack of accurate and effective fire risk assessment tools tailored to CCF environments hinders proactive forest management and conservation efforts. Therefore, the research problem centres on developing and evaluating machine learning techniques to accurately assess fire risk in CCF forests, leveraging a combination of real-world meteorological data and simulated forest-specific variables..

## **1.1.2 Hypothesis**

The hypothesis for this study is that by integrating advanced machine learning techniques with a combination of real-world meteorological data and simulated forest-specific variables, it is possible to develop a highly accurate and effective fire risk assessment model for CCF forest in Ireland.

## **1.1.3 Research Objectives Rewrite next**

To construct a predictive model for fire risk in CCF, we set forth the following objectives:

1. Review of Existing Methodologies: Conduct a comprehensive review and critique of current fire risk assessment methods, focusing on their applicability to CCF setting in Ireland. Identify ley criteria and variables relevant to fire assessment in CCF forest to inform the development of an enhanced predictive model.
2. Integrated Meteorological data from the Copernicus Emergency management Service and simulated CCF forest-specific variables to create a comprehensive dataset for fire risk assessment in CCF forests. This integration will provide insight into atmospheric conditions and forest characteristics crucial for assessing fire danger levels and formulating effective mitigation strategies.
3. Development of Machine Learning Predictive Model: Utilize machine learning techniques, including Knearest Neighbours (KNN), XGBoost, Random Forest, Decision Tree, and support Vector Machines (SVM), to develop a sophisticated predictive model for fire risk assessment in CCF Forests. Rigorous hyperparameter tuning and cross- validation will be employed to optimise model performance and ensure robustness in handling complex relationships and diverse datasets.
4. Decision-Support Tool Development: Transform the developed predictive model into a user friendly decision-support tool tailored for forest managers and policy makers. This tool will integrate advanced analytics into an interactive interface, providing actionable insights for fire risk mitigation in CCF landscapes. Scenario-based simulations ill demonstrate the practical utility of the tool in real world forest management scenarios.

In summary, the objectives outlined in this study are closely aligned with the theme in the overarching proposed title, “Machine Learning-Driven Fire risk Assessment in continuous Cover Forestry: Enhancing predictive Capabilities for sustainable Management”. These objective collectively map out a comprehensive path toward developing, validating, and deploying a robust machine learning model tailored to address the critical need for advanced fire risk assessment methodologies in Continuous Cover Forestry (CCF) settings. Bu conducting a thorough review of existing methodologies, constructing sophisticated predictive models establishing a rigours validation framework, and creating an intuitive decision-support tool, this research aims to redefine how fire risks are managed in CCF landscapes. Through the integration of meteorological data with simulated forest-specific variables, the endeavour seeks to provide actionable insights that empower stakeholders to proactively mitigate fire risks, ultimately contributing to the sustainable stewardship and conservation of forest ecosystems in Ireland and beyond.

# **2. Literature Review**

## **2.1 Introduction to Fire Risk Assessment in Forestry**

Fire risk assessment methodologies are fundamental in forestry for predicting and mitigating the impact of wildfires (Dennison et al., 204). In the unique (Thompson and Calkin, 2011). The literature review summary table (Figure 1) offers succinct overview of seminal studies and their methodologies, providing valuable insights into the diverse approaches in fire risk assessment research |Dimuccio et al., 2011; Crimmins 2006; Bisquert et al., 2012). This section aims to comprehensively review current fire risk assessment methods, specifically focusing on their applicability to CCF settings in Ireland. Key criteria and variables employed in these methodologies, encompassing fuel characteristics, weather conditions, topography and human factors, are critically evaluated to facilitate the development of improved predictive models. Studies by McCarthy et al. (2002), Pommerening and Murphy (2004), and Thompon and Calkin (2011) have contributed significantly to our understanding of these factors.

Traditionally fore risk assessment methods in forestry rely on empirical data, statistical models, and expert knowledge. These methods often incorporate and spread wildfires. For instance, Stocks et al. (19890 discussed the Canadian Fores Fire Danger Rating System (CFFDRS), which integrates weather conditions, topography, and vegetation types to determine fire danger indices. Similarly , Deeming et al. (1997) outlined the National Fire Danger Rating System (NFDRS) used in the United States. However, the applicability of these methods to CCF settings in Ireland is limited due to the heterogeneous nature of CCF forests. This is a point supported by O’ Sullivan et al. (2017), who identified limitations of traditional methods in CCF contexts. European studies also contribute significantly to the understanding of fire risk assessment methodologies. For instance, San-Miguel-Ayanz et al. (2012) discussed the European Forest Fire Information System (EFFIS), which aids fire management by integrating satellite data and ground based observations to provide near-real-time monitoring of fire events. Modugno et al. (2016) explored the impact of climatic differences on fire risk assessment, emphasizing the importance of tailoring strategies to local conditions.

**Figure 1 Literature review summary table**

|  |  |  |
| --- | --- | --- |
| **Authors** | **Article Title** | **Methodologies/ Tools** |
| Bisquert et al. (2012) | Application of artificial neural networks and logistic regression to the prediction of forest fire danger in Galicia using MODIS data | Artificial Neural Networks(ANN), Logistic Regression |
| Cao et al. (2017) | Wildfire susceptibility assessment in southern China: A comparison of multiple methods | Gradient Boosted Decision Trees (GBDT) |
| Chuvieco et al., 2010 | Development of sophisticated fire susceptibility models | Geographic Information Systems (GIS), Layering and spatial analysis of various datasets, integration of topographical data. |
| Crimmins, 2006 | Synoptic climatology of extreme fire-weather conditions across southwest United States | Artificial Neural Networks(ANN), Logistic Regression, Logistic Tree. |
| Eidenshink et al., 2007 | Utilising satellite remote sensing technology for evaluating burn severity and extent | Monitoring Trends in Burn Severity (MTBS) project, satellite imagery |
| Kumar & Kumar, 2020 | Applications of data science in bushfire risk assessment in Australia | Integration of machine learning with remote sensing, mapping, fuel loads, predicting fire behaviour across diverse terrains. |
| Oliveira et al. (2012) | Modelling spatial patterns of fire occurrence in Mediterranean Europe using multiple regression analysis | Gradient Boosted Decision Trees (GBDT) |
| Rodrigues and de la Riva, 2014 | Enhancing prediction of forest fire likelihood | Machine Learning algorithms (e.g., ANN, SVM), analysis of extensive datasets including weather variables, vegetation types |
| Sakr, 2016 | Addressing challenges in data volume and computation for accurate predictions | Requirement of significant computational power, algorithms for efficient data processing, handling of large datasets |
| Viegas et al., 2018 | Advancements in fire risk assessment | Machine Learning algorithms (e.g., ANN, SVM) surpassing conventional statistical methods |

## **2.2 Traditional Fire Risk Assessment Methods**

Fire risk assessment in forestry has traditionally relied on a combination of empirical data, statistical models, and expert knowledge. Conventional methods often use historical fire data to identify patterns and factors most frequently associated with the initiation and spread of wildfires. These methods have been integrated into various fire danger rating systems globally, like the Canadian Forest Fire Danger Rating System (CFFDRS) and the National Fire Danger Rating System (NFDRS) used in the United States (Stocks et al., 1989; Deeming et al., 1977) and the McArthur Forest Fire Danger Index (FFDI) utilized in Australia Fire risk assessment tools usually include factors such, as weather conditions (like temperature, wind speed, humidity) topography and vegetation types to determine a fire danger index. It is evident that there is a requirement for the creation of tools and approaches that can overcome the restrictions of fire risk assessments and offer dependable information, for managing CCF in Ireland (Thompson and Calkin 2011). In more traditional forestry practices that are characterized by uniform stand structures and species compositions, such methods have been effective in predicting areas of high fire risk and in guiding fire prevention efforts (Andrews et al., 2005). However, when evaluating their effectiveness in Continuous Cover Forestry, the limitations of traditional fire risk assessment methods become apparent. These methos assume that the fuel is uniformly distributed and behaves in a predictable way, which is not the case in CCF (Zumbrunnen et al., 2011). Furthermore, the microclimate variations within CCF stands, a result of the canopy complexity, can significantly influence fore behaviour in ways that traditional models may not accurately capture (Agee, 2013). Another limitation is the temporal resolution of traditional assessment methods. While these methods are suitable for short-term fire risk predictions, they are less effective for long-term risk assessments, which are essential for planning in the context of CCF where the forest structure is managed over extended periods (Fernandes and Botelho, 2003). Challenges also arise from the scale at which these models operate. Traditional methods often work at larger scales and may not provide the fine-scale resolution necessary for managing CCF plots, where individual tree selection and small-scale challenges, particularly in regions where fire occurrences are low or where fire suppression efforts have been highly effective, resulting in a lack of data to inform risk models. This data limitation is further compounded in CCF systems, where historical fire data may be non—representative of current conditions due to changes in forest management practices over time (McCarthy et al., 1999). While traditional fire risk assessment methods have provided a foundation for understanding and managing wildfire risk in conventional forestry practices, their limitations are pronounced in the context off CCF. The complexity and variability inherent in CCF require more nuanced and dynamic modelling approaches that can accommodate the unique features of these forests.

## **2.3 Data Science Applications in Environmental Risk Assessment**

Data science has notably transformed environmental risk assessment by enriching the analysis, prediction, and management processes with advanced technological tools. Leveraging big data analytics, machine learning (ML), and spatial analysis has unlocked deeper insights into complex environmental risks. The multifaceted approach of data science in this field encompasses diverse methodologies. For instance, machine learning algorithms have significantly enhanced the prediction of forest fire likelihood through the examination of extensive datasets comprising weather variables, vegetation types, and historical fire instances (Rodrigues and de la Riva, 2014). Techniques like artificial neural networks (ANNs) and support vector machines (SVMs) offer a rapid and precise assessment of fire risks, outpacing conventional statistical methods (Viegas et al., 2018). A case in point is the application of data science in assessing bushfire risks in Australia, where the integration of machine learning with remote sensing has facilitated the mapping of fuel loads and fire behaviour prediction across diverse terrains (Kumar & Kumar, 2020). Furthermore, satellite imagery and advanced data processing tools have become instrumental for real-time fire monitoring and for strategic deployment of firefighting resources. In the United States, projects like Monitoring Trends in Burn Severity (MTBS) employ satellite remote sensing technology to evaluate the severity and extent of burns, which enriches the understanding of fire effects on ecosystems and supports the rehabilitation of areas impacted by fires (Eidenshink et al., 2007). Innovations in geographic information systems (GIS) have enabled the layering and spatial analysis of various data sets, culminating in sophisticated fire susceptibility models that integrate topographical, meteorological, and human factors to present a holistic view of landscape-level fire risks (Chuvieco et al., 2010). Additionally, the Internet of Things (IoT) has revolutionized risk assessments, with sensor networks in forests delivering real-time environmental data to facilitate dynamic risk modelling responsive to changes in factors like temperature and humidity (Divya et al., 2019). Despite these advancements, the field faces considerable challenges, particularly in the realms of data volume and computation. Accurate predictions require significant computational power and algorithms designed for efficient data processing (Sakr, 2016). Moreover, the validity of these models hinges on the quality and granularity of the data, which can be variable based on the source. Data science has made a profound impact on environmental risk assessment. The sophistication and efficacy of these tools have not only improved the accuracy and response times of analyses but are also set to become more central in environmental risk management, especially regarding forest fires and similar natural threats.

## **2.4 Comparative Analysis of Fire Risk Assessment in Different Geographies**

Fire risk assessment strategies vary globally, reflecting the diverse climatic conditions, forest management practices, and technological capabilities of different regions. This section explores these strategies with a particular focus on countries like Ireland, Canada, Australia, and other European nations, and how local conditions influence fire risk assessment. In Ireland, fire risk assessment for forestry has historically been less of a concern compared to countries with a more prevalent fire regime. However, climate change and shifts in land use are altering fire dynamics, necessitating a revaluation of risk assessment (Prutsch et al., 2014). The Irish strategy now includes using meteorological data to forecast fire weather, incorporating these data into fire danger rating systems adapted from models like the Canadian Forest Fire Weather Index (FWI) System (DAFM). Canada, with its vast boreal forests, is well-acquainted with wildfires, and the country has developed one of the most advanced fire danger systems in the world. The Canadian FWI system is a comprehensive tool that uses weather data to estimate fire danger and has been adapted by many countries due to its reliability (Wotton et a., 2010). Its ability to account for regional differences unweather and vegetation makes it a versatile tool for fire risk assessment Similar to Canada, Australia faces significant wildfire threats across its varied landscapes, from tropical savannas to temperate eucalypt forests known for their flammability. The country has developed its fire danger rating systems, which include the McArthur Fire Danger Index and the Australian Fire Danger Rating System, using local climate data, vegetation types, and fire behaviour research. These systems are essential for providing fire danger warning to both the public and fire management authorities in a country that experiences frequent and severe bushfires (Tian et al., 2005).

In Europe, countries experience a diverse set of fire environments, from the Mediterranean's fire-prone ecosystems to the less fire-affected forests of central and northern Europe. The European Forest Fire Information System (EFFIS) aids fire management by integrating satellite data and ground-based observations to provide near-real-time monitoring of fire events (San-Miguel-Ayanz et al., 2012), playing a vital role in harmonizing fire risk assessment across the continent's diverse landscapes.

The impact of climatic differences on fire risk assessment is critical. The dry, hot summers of Mediterranean Europe and Australia's bushfire-prone regions create conditions conducive to wildfires, in stark contrast to the cooler, wetter climate of northern Europe and Ireland, resulting in lower fire incidence. These climatic factors, along with geographical variations such as topography and road networks, significantly influence fire behaviour and risk assessment (Modugno et al., 2016). Management practices also play a significant role in shaping fire risk assessments. For instance, the traditional 'fight fire with fire' techniques employed by some Canadian First Nations and Australian Aboriginal cultures, which use controlled burns to manage the landscape, contrast with the fire suppression policies historically prevalent in European forestry (Traditional Aboriginal Burning, 2013). Fire risk assessment strategies must be tailored to local conditions, incorporating climatic, geographical, and management factors. By learning from the varied approaches of countries like Ireland, Canada, Australia, and those in Europe, stakeholders can develop more effective, context-specific risk assessments. The adaptive capacity of fire risk assessment systems, such as the Canadian FWI, Australia’s national frameworks, and Europe's EFFIS, serves as models for countries worldwide as they confront the evolving challenges posed by climate change on fire regimes.

## **2.5 Advancements in Predictive Analytics and Modelling for Fire Risk Assessment**

Advancements in predictive analytics have become a cornerstone for fire risk assessment, particularly with the fusion of machine learning and environmental science. The transformative impact of deep learning (DL), such as the implementation of Recurrent Neural Networks (RNNs) and Long Short-Term Memory networks (LSTMs), is evident in their capacity to process and analyse the sequential and temporal dynamics of fire-related datasets, leading to nuanced modelling of fire risk progression over time (Heaton et al., 2017). Ensemble models, employing both bagging and boosting techniques, have significantly improved prediction accuracy by mitigating the variance and bias commonly associated with more simplistic models, thereby delivering a robust predictive performance (Breiman, 2001). Additionally, time series forecasting methods, including Autoregressive Integrated Moving Average (ARIMA) models, leverage historical fire occurrence and climatic data to forecast future fire risks with enhanced precision (Box et al., 2015). The integration of big data in fire risk analytics has offered unprecedented scope and scale in monitoring and assessment. Satellite imagery from MODIS and VIIRS has been instrumental in providing daily updates on surface temperatures and vegetation health, key factors in determining fire risk (Justice et al., 2002). Concurrently, the deployment of Internet of Things (IoT) technologies has facilitated the real-time acquisition of crucial environmental parameters, such as soil moisture levels and canopy temperatures, directly impacting the precision of fire potential assessments (Ray, 2017). Real-time data processing, facilitated by edge computing, marks a pivotal enhancement in fire management strategies. By processing sensor and satellite data at or near the source, edge computing dramatically reduces latency, thereby supporting swift and informed decision-making during critical fire episodes (Shi et al., 2016). Furthermore, streaming analytics platforms can digest and interpret data streams in real time, offering immediate insights into fire behaviour and enhancing the efficiency of early warning systems (Zaharia et al., 2013). Noteworthy case studies exemplifying the use of advanced analytics in fire risk assessments include the AI-driven prediction models employed during California's Camp Fire in 2018, which utilized live data streams for predicting the fire's trajectory, thus facilitating timely evacuations (Kaggle, 2018). Similarly, in Brazil, fire risk models incorporating climate data and utilizing Support Vector Machines (SVMs) have shown substantial success in predicting fire incidences with high accuracy (Maeda et al., 2011). Despite these advancements, the integration of sophisticated predictive models in fire risk assessment is not without challenges. The validity and detail of data can influence the accuracy of predictions, while the computational intensity required for processing extensive datasets and executing intricate simulations necessitates robust computational infrastructure (Dean et al., 2008). Moreover, there exists a critical need for interdisciplinary expertise to effectively translate complex model outputs into actionable fire management strategies, necessitating collaboration between data scientists and fire management experts (Kolden et al., 2015).

In this this examination of methodologies for modelling fire occurrence, we assess the effectiveness and implications of various approached across different geographic regions. Dimuccio et al. (2011) combined artificial neural networks (ANN) and logistic regression to discern regional forest-fire susceptibility in central Portugal, offering robust assessment by combining probabilistic ratings and ANN weights assignments. Bisquert et al. (2012) underscored the superior predictive accuracy of ANN over logistic regression in predicting forest fire danger maps. Cao et al. (2017) demonstrated the efficacy of the cost-sensitive Random Forest algorithm for wildfire susceptibility assessment in Southern China, emphasising the significance of factors such as forest coverage ratio, seasonality, and environmental condition. Oilveria et al. (202) compared traditional Multiple Layer Regression and Random Forest methods for modelling spatial patterns of fire occurrence in Mediterranean Europe, revealing the latter’s superior performance and identifying crucial influencing factors such as precipitation, soil moisture, and socio- economic variables. Crimmins (2006) study highlights the Random Forest model’s heightened predictive ability for analysing extreme fire-weather conditions in the southwest United States, contributing to a nuanced understanding of weather-fire interactions. Bui et al. (2017) demonstrated the efficacy of a hybrid artificial intelligence approach for forest fire susceptibility modelling in tropical regions, highlighting the importance if integrating methodologies for accurate risk assessments. Satir and Ercan (2016) provided valuable insights into regional forest fire probability in Mediterranean ecosystems using ANN models, including key landscape features correlated with fire occurrence. Arpaci et al. (2014) emphasised the significance of multivariate data mining techniques for estimating fire susceptibility of Tyrolean Forests, informing land management strategies and limitations of different modelling approaches, paving the way for proactive fire risk strategies tailored to specific environmental contexts. These findings underscore the importance of advanced methodologies in fire risk assessment, emphasising the need for tailored and proactive mitigation strategies. This understanding forms a strong foundations for developing effective fire management approaches, particularly relevant to fire risk assessment in forestry, and within CCF forest settings in Ireland. Looking to the future, predictive analytics in fire risk management is expected to evolve towards the utilization of AI with Unmanned Aerial Vehicles (UAVs) for meticulous data collection and nuanced risk assessments (Sudhakar et al., 2020). The prospect of developing autonomous fire detection systems employing satellite and drone technologies promises a leap forward in rapid response capabilities. Furthermore, integrating AI with comprehensive climate models can provide valuable foresight into the long-term effects of climate change on fire risk, enabling more effective preparation and mitigation strategies (Amatulli et al., 2013). This holistic approach to predictive analytics signifies a profound shift in fire risk assessment, propelling it towards a future where data-driven insights drive proactive, rather than reactive, fire management strategies. These advancements collectively represent a step change in our capability to predict, manage, and reduce the risks associated with wildfires, showing the potential of technology to safeguard natural resources and communities alike.

**Figure 2 Suitability of methods in forest fire modelling according to previous studies**

|  |  |  |  |
| --- | --- | --- | --- |
| **Method used** | **Best Method** | **Study Area** | **References** |
| **Artificial Neural Networks (ANN)** | **Logistic Regression** | **Central Portugal** | **Dimuccio, L. A., Salis, M., Ager, A. A., & Finney, M. A. (2011). Regional forest-fire susceptibility analysis in central Portugal using a probabilistic ratings procedure and artificial neural network weights assignment. International Journal of Wildland Fire, 20(6), 776-791.** |
| **Artificial Neural Networks (ANN), Logistic Regression** | **Artificial Neural Networks** | **Galicia , Spain** | **Bisquert, M., Lopes, A., & Nunes, J. (2012). Application of artificial neural networks and logistic regression to the prediction of forest fire danger in Galicia using MODIS data. International Journal of Wildland Fire, 21(8), 1025-1029.** |
| **Artificial Neural Networks (ANN), Logistic Regression** | **Artificial Neural Networks, Logistic Regression** | **Various regions in Europe** | **Bui, D. T., Pradhan, B., Lofman, O., Revhaug, I., Dick, Ø. B., & Pham, B. T. (2017). A hybrid artificial intelligence approach using GIS-based neural-fuzzy inference system and particle swarm optimization for forest fire susceptibility modelling at a tropical area. Agricultural and Forest Meteorology, 233, 32-44.** |
| ***Artificial Neural Networks (ANN), Logistic regression*** | ***Artificial Neural Networks (ANN), Logistic regression*** | **Tyrolean forest, Austria** | **Arpaci, A., Çölkesen, İ., Koç, A., & Buyuksalih, G. (2014). Using multivariate data mining techniques for estimating fire susceptibility of Tyrolean forests. *Applied Geography, 53*, 258-270.** |
| ***Decision Tree, Support Vector***  ***Machines (SVM)***  ***Naïve Bayes,***  ***Decision Tree*** | ***MLP-CNN***  ***Decision Tree, SVM*** | ***Southern China*** | **Cao, Y., Li, J., Wang, Q., Chen, Y., & Luo, J. (2017). Wildfire susceptibility assessment in Southern China: A comparison of multiple methods. *International Journal of Disaster Risk Science, 8*(2), 164-181.** |
| ***Gradient Boosted Decision Trees (GBDT)*** | ***Gradient Boosted Decisions Trees*** | ***Various regions*** | **Oliveira, S., Oehler, F., & San-Miguel-Ayanz, J. (2012). Modelling spatial patterns of fire occurrence in Mediterranean Europe using Multiple Regression and Random Forest. *Forest Ecology and Management, 275*, 117-129.** |

## **2.2 Variables and Criteria in Fire Risk Assessment**

Fire risk assessment in forestry relies on the analysis of various variables and criteria to predict and mitigate the impact of wildfires. Fuel characteristics encompassing the type, quantity, arrangement and moisture content of fuels such as vegetation and deadwood, play a pivotal role in determining fire behaviour, as highlighted by Clarke et al. (2014).Meteorological factors, including temperature, humidity, wind speed, and precipitation, significantly influence fire behaviour and spread, as demonstrated by Tian and Liu (2011). Modungo et al. (2016) explored the impact of climatic differences on fire risk assessments, emphasising the importance of tailoring strategies to local conditions. Similarly FAO(2018) advocated for integrating real-time meteorological data to enhance fire risk assessments. Long term climate patterns and trends, identified by Ganteaume et al. (2013) and Seager et al. (2015), also affect fire regimes and contribute to variations in fire occurrence and severity. Topography comprising terrain features like slope, aspect, and elevation, also plays a critical role in shaping fire behaviour and severity, as evidenced by studies such as Pommerening and Murphy (2204). Human factors, encompassing human activities and land use practices, further influence fire risk, as explored by Thompson and Calkin (2011) and McCarthy et al.(2006). Pommerening and Murphy(2004) examined the role of topographical features such as slopes and elevation in influencing fire behaviour. Additionally, the compositions and arrangement of land cover types, such as forest, grasslands, and urban areas, impact fire behaviour and spread, as indicated by Nunes et al. (2005). Additionally, characteristics of combustible material and terrain factors, as highlighted by Tiam and Liu (2011), provides valuable insights into fire dynamics and informs fire risk assessments. Recent studies have shown that forest fire spread is influenced by various factors, including climatic factors, terrain, combustible material, and land cover types (Keenan, 2015). These variables and criteria collectively contribute to comprehensive understanding of fire risk in forestry, guiding the development of effective strategies for fires preventions, mitigations and management.

Fire risk assessment methodologies in forestry encompass a broad range of factors influencing the likelihood and severity of wildfires. Figure 3 presents an overview of variables and criteria commonly utilized in fire risk assessment, adapted for the context of CCF forests.

**Figure 3 Variables and Criteria in Fire Risk Assessment**

|  |  |  |
| --- | --- | --- |
| **Category** | **Description** | **References** |
| **Climate Factors** | Long-term climate patterns and trends | Ganteaume rt al, (2013), Seager et al. (2015) |
| **Combustible factors Variables** | Characteristics of combustible material | Tian and Liu (2011) |
| **Fuel Characteristics** | Type, quantity, arrangement, and moisture content of vegetation and deadwood. | Clarke et al, (2004) |
| **Historical Data** | Data on past fire occurrences and behaviour | Keenan (2015), Tian and Liu (2011), Fhad et al.(2021). |
| **Human Factors** | Influence of human activities and land use practices | Thompson and Calkin (2011), McCarthy rt al. (2006) |
| **Land Cover Type** | Influence of composition and arrangement of land cover types | Nunes et al (2005), Clarke et al. (2004) |
| **Land Use Practices** | Influence of human land use practices | Thompson and Calkin (2011), McCarthy et al. (2006) |
| **Terrain Factors** | Role of topographical features in influencing fire behaviour | Pommerening and Murphy (2004) |
| **Topography** | Impact of terrain features like slop, aspect, and elevation | Pommerening and Murphy(2004) |
| **Weather Conditions** | Influence of temperature, humidity, wind speed, and precipitation | Tian and Liu (2011),FOA (2018), Modungo et al. (2016) |

In CCF systems, unique criteria and variables influence fire risk differently compared to traditional forest management practices. Figure 4 presents an overview of these unique criteria alongside general forest variables and risk factors

**Figure 4 Unique Criteria and Variables in CCF and their Vulnerability to Fire**

|  |  |  |  |
| --- | --- | --- | --- |
| **Variable/ Criteria** | **Description** | **Vulnerability to Fire** | **References** |
| Canopy Density | Density and arrangement of tree canopies, influencing light penetration and understory growth | Higher canopy density can increase the risk of crown fires and vertical fire spread | Wilson et al. (2018a), Wilson et al(2018b) |
| *Continuous Canopy Cover* | *Maintenance of canopy cover throughout stand development, impacting biodiversity and soil conservation* | *Continuous canopy cover can create continuous fuel beds, increasing fire continuity and potential spread* | *The Irish Forest Service(2018), Wilson et al. (2018a)* |
| *Multi-aged Stands* | *Presence of trees of different ages within the same stand, influencing habitat diversity and ecosystem stability* | *Variations in tree ages can create diverse fuel structures, affecting fire behaviour and spread rates* | *Wilson (2009),* Wilson and Ní Dhubháin (2020 |
| *Natural regeneration* | *Regeneration of trees through natural processes, influencing stand composition and age structure* | *Uneven age distribution resulting from natural regeneration can lead to variations in fuel loads and fire behaviour,* | *Byrne and Farrell (2005), Laacke and wilson(2010)* |
| *Stand Structure* | *Vertical and horizontal arrangment of tree crowns and stems, influencing microclimate and fuel arrangements* | *Complex stand structures may create varied fuel arrangements, potentially increasing fire intensity and difficulty of control* | Wilson and Ní Dhubháin (2020), Wilson and O’Tuama (2019) |
| *Tree Species Diversity* | *Diversity of tree species impacting fuel characteristics and fire behaviour* | *Monoculture stands or lack of diversity may increase susceptibility to specific pests or diseases, leading to increased fuel loads and fire risk* | *Wilson(2009), Wilson and O’Tuama (2019)* |
| *Understory Structure* | *Composition and arrangement of understory vegetation affecting fuel continuity and fire behaviour* | *Dense understory vegetation can contribute to ladder fuels, facilitating fire spread from the forest floor to the canopy* | *Byrne and Farrell (2005), Laacke and wilson(2010)* |

## **2.6 Economic and Social Implications of Fire Risk in Irish CCF Systems**

In Ireland, the adoption of Continuous Cover Forestry systems carries distinct economic and social implications, particularly when considering the risk of wildfires. Economically, fire incidents within CCF landscapes can incur substantial costs, including those associated with challenging suppression efforts due to the complex forest structures promoted by CCF principles. Moreover, such fires threaten significant revenue losses from the destruction of commercially valuable timber, adversely affecting the livelihoods of those dependent on forestry in rural areas **(Ní Dhubháin et al., 2023).** The potential for damage to CCF areas also poses threats beyond immediate timber losses. It compromises the broader ecological benefits, such as carbon sequestration, which is crucial for Ireland's climate action targets **(Ní Dhubháin et al., 2009).** Additionally, wildfires can have detrimental effects on tourism, which is vital to the rural economy, as areas of natural beauty and recreational forests are rendered inaccessible or less appealing post-fire (Prestemon et al., 2016). Socially, the ramifications extend to public health concerns, notably when peatlands, which are prevalent in Irish landscapes, catch fire. The smoke and particulate matter from burning peat have been associated with respiratory problems and other health risks, necessitating attention in fire management policies (Rein et al., 2008). Though large-scale evacuations are less common in Ireland due to the smaller size of forested areas, the social fabric of rural communities can still be disrupted by fireincidents, affecting residents' sense of security and community cohesion **(Ní Dhubháin et al., 2023)**. In conclusion, Ireland’s CCF systems must navigate the fine balance between sustainable forest management and the heightened risk of wildfires. The economic and social stakes highlight the need for tailored fire management strategies that align with the intricate dynamics of CCF, thereby safeguarding not only the forests but also the communities that surround and depend upon them.

## **2.7 Policy and Regulatory Frameworks Impacting Fire Management in Irish CCF**

In Ireland, the policy and regulatory landscape is a fundamental component that dictates fire management approaches within Continuous Cover Forestry (CCF) systems. The Forest Service, operating under the Department of Agriculture, Food, and the Marine, oversees efforts to prevent and control forest fires, with regulatory power granted by key legislation such as the Forest Act and the Wildlife Acts. These statutes outline the legal parameters for conducting prescribed burns and establish punitive measures for the initiation of illegal fires (Forest Service, 2017). The integration of predictive analytics into fire risk assessment is shaped by regulatory frameworks like the Fire Weather Index (FWI) in Ireland and the National Forest Fire Danger Rating System (NFFDRS). While FWI focuses on weather conditions and fuel moisture content, NFFDRS considers additional factors like topography and vegetation type (DAFM). However, implementing predictive tools faces challenges, including the need for current fire management strategies to evolve and compliance with EU environmental directives (Forest Service, 2020). To harness the full potential of these technologies, regulatory frameworks need to be dynamic and forward-looking. The Forestry Programme 2014-2020, for instance, has laid down provisions to bolster forest protection that could be further developed to embrace advanced analytics and other contemporary fire management technologies (Forest Service, 2020). Effective integration also hinges on cross-departmental and interagency collaboration (Carvalho et al., 2016), which is crucial to crafting comprehensive policies that support the application of the best available technology within CCF practices. In embracing advanced predictive analytics through deliberate policy measures and regulatory frameworks, Ireland can significantly enhance the capacity of its CCF systems to withstand the increasing wildfire threat, while also contributing to global best practices in sustainable forest management

## **2.8 Gaps and Limitations in Current Research**

Despite the significant advancements in fire risk assessment within Continuous Cover Forestry (CCF), the literature reveals persistent gaps and limitations that need to be addressed to enhance predictive capabilities and management interventions. One of the notable gaps is the limited research on the specific application of fire risk assessment tools in CCF systems. Most fire risk models have been developed for and tested within conventional forestry settings, where clear cutting and even-aged stand structures predominate. CCF's complex forest structures, with their continuous canopy and multi-aged stands, present unique fire behaviour that is not adequately captured by these models (Pretzsch, 2014). This highlights the need for developing or adapting models that can account for the intricacies of CCF. Another gap is the integration of climate change projections into fire risk assessment. While climate models predict increased fire weather severity, integrating these projections into risk models remains challenging due to the uncertainties associated with climate models and the long-term nature of forest planning (Balshi et al., 2009). The slow incorporation of this data , as highlighted by Abatzoglou and Willimas (2016), undermines the potential for current assessments to anticipate future fire regimes accurately. The variability in data collection scales, as evidenced by Shephard and Keeley (2015), also presents a limitations of data collection also presents a limitation. Much of the forest fire data in general are collected at a macro scale as highlighted in a study by , which can dilute the specific conditions encountered in CCF areas. The lack of fine-scale, high-resolution data impedes the ability to conduct nuanced analyses, as discussed by Hudak et al. (2008), impedes the ability to conduct nuanced analyses that are essential for CCF areas, which are heterogeneous by nature. Furthermore, there is a scarcity of longitudinal studies that evaluate the long-term effectiveness of fire risk reduction strategies in CCF contexts. Presler er al. (2004) highlight the importance of probability-based models for estimating wildfire risk, emphasising the need for such longitudinal studies to understand the temporal dynamics of fire risk and sustained impacts of management interventions. Without this information, it is challenging to develop adaptive management strategies that evolve with changing forest conditions and risk profiles. The literature also points to limited understanding of socio-economic dimensions of fire risk in CCF. While ecological and climatic factors have received considerable attention, the human dimension, including public perception, economic impacts, and policy considerations, is less well-studies within the context of CCF (Ní Dhubháin et al., 2006). As such, there is a need for holistic approaches that incorporate these factors into fire risk assessment and management. In terms of methodological limitations, there is a reliance on historical fire data to predict future risks. However, as Bowman et al. (2009) highlights, given the dynamic nature of the \Earth system and the impacts of factors like climate change and land use patterns past fire regimes may not reliably forecast future conditions. Therefore, there is a need for forward-looking approaches that cab adapt to changing environmental and human landscapes. Lastly, while data science techniques offer promising avenues for enhancing fire risk assessment, the integration of these techniques into operational settings is still in its infancy. Challenges such as data availability, computational resources, and the need for interdisciplinary expertise hinder the operationalization of these advanced methods (San-Miguel-Ayanz et al., 2013). In summary, the current body of literature on fire risk assessment in CCF forests in Ireland shows significant gaps and limitations that must be addressed. The development of models specific to CCF, incorporation of climate change projections, collection of fine-scale data, longitudinal studies, consideration of socio-economic factors, forward-looking predictive methods, and operational integration of data science techniques are all areas that require further research and attention.

## **2.9 Justification for the Present Study**

Forest fires in CCF forest settings in Ireland present unique challenges due to their continuous canopy cover and multi-aged stands, which standard fire risk models struggle to address effectively . Current literature emphasizes the necessity for advanced methodologies capable of accounting for the intricacies of Irish CCF landscapes. Additionally, climate change projections suggest an increased likelihood of extreme fire conditions, highlighting the urgency to improve fire risk assessment strategies. Data science offer a promising solution, with its capacity to process complex datasets and provide valuable insights into fire behaviour ( Joyce & Rodman, 2018). Integrating heterogenous data sources, such as meteorological data and forest-specific variables, can enhance the accuracy of fire risk assessment in CCF forests. However, the current literature lack sufficient research specifically tailored to CCF contexts in Ireland, underscoring the need for empirical studies in this are. This study aims to fill this gap by exploring the application of machine learning techniques for fire risk assessment in CCF Irish forests, thereby contributing to the advancement of fire management strategies in these ecosystems.

# **3. Methodology:**

Every Supervised learning Project has an overall methodology (Figure 5):

Figure 5 Methodology

A diagram of a machine learning algorithm

Description automatically generated

The Process includes:

* Data Extraction
* Data Cleaning
* Label Encoding
* Handling Imbalanced Data
* Exploratory Data Analysis
* Feature Engineering
* Data Splitting and Scaling
* ML Algorithms
* Results Evaluations  
  Each rectangle is representing a process and the relation between each process is given as process flow(arrow is representing the flow). We will discuss each process in detail in the next sections.

**Data Flow Diagram**

The process flow diagram involves the several processes given in fig 6.

A diagram of a data flow

Description automatically generated

Figure 6 Data Flow Diagram

Explanation

**User:**

Explanation: The process begins with the user, who initiates the entire workflow. The user may be involved in specifying requirements, providing input data, or interacting with the system in many ways.

**Datasets:**

Explanation: The Datasets step involves gathering and preparing the data required for the forest fire risk assessment. This could include historical weather data, simulated forest data, or any other relevant information needed to train and evaluate the machine learning model.

**Preprocessing:**

Explanation: In the Preprocessing step, the collected datasets undergo data cleaning, transformation, and feature engineering. This ensures that the data is in a suitable format for training the machine learning model. Preprocessing may involve handling missing values, scaling features, or encoding categorical variables.

**Model Training:**

Explanation: Model Training is where the machine learning model is developed using the pre-processed datasets. The model learns patterns and relationships from the data, allowing it to make predictions about forest fire risk based on input features.

**Evaluation:**

Explanation: After training, the model's performance is evaluated using a separate dataset not seen during training. Evaluation metrics such as accuracy, precision, recall, or F1 score are used to assess how well the model generalizes to new, unseen data. The Evaluation step is connected to the Evaluation Results for a comprehensive understanding of the model's performance.

**Model Selection:**

Explanation: In Model Selection, different machine learning models or variations of the same model are compared based on their performance during evaluation. The goal is to choose the most effective model for predicting forest fire risk.

**Deployment:**

Explanation: Once a suitable model is selected, it is deployed for use in real-world scenarios. Deployment involves integrating the model into a system or application, making it accessible for generating predictions based on new input data.

**Real World Predictions:**

Explanation: The deployed model is now capable of making real-world predictions. It takes input data relevant to forest conditions, weather, or other parameters and produces predictions about the likelihood of a forest fire occurring.

**End:**

Explanation: The process concludes with the End step, signifying the completion of the workflow. Users can now leverage the forest fire risk assessment system to obtain predictions and insights based on the deployed machine learning model. The interconnected flow ensures a seamless transition between each stage, enhancing the overall effectiveness of the forest fire risk assessment system.

## **3.1 Data Collection:**

In this Project we must use two dataset’s details of the datasets are given below:

## **3.1.1 CD's API Data:**

The dataset obtained from the Copernicus Emergency Management Service provides a comprehensive historical reconstruction of meteorological conditions conducive to the initiation, propagation, and sustainability of fires. This dataset is an integral component of the European Forest Fire Information System (EFFIS) and encompasses fire danger metrics based on models developed in Canada, the United States, and Australia. The fire danger indices within this dataset are calculated using weather forecasts derived from historical simulations provided by the ECMWF ERA5 reanalysis. ERA5, a globally complete and consistent dataset, combines model data with quality-controlled observations, making it a reliable proxy for observed atmospheric conditions. The dataset includes variables such as the Build-Up Index, Burning Index, Danger Rating, Drought Code, Energy Release Component, Fine Fuel Moisture Code, and various others. These variables play crucial roles in assessing fire danger levels and formulating fire danger forecasts for pre-suppression planning. These factors make the dataset a valuable resource for studying and mitigating forest fire risk in Ireland.. This choice was made over other options due to its comprehensive coverage, reliability, and integration within established frameworks of fire management. By isolating Ireland for analysis, it ensured a focused and comprehensive approach to understanding and mitigation forest fire risk in the country. Furthermore, while options like the Global Fire Weather Database and Global Forest Watch Fire Monitoring provide valuable meteorological data, they lack forest specific parameters necessary for our research objectives . Given the need for a tailored approach to forest fire assessment in Ireland, these alternatives were deemed less suitable. Additionally, the Irish Fire Weather Index (FWI) was not utilized due to its focus on general fire weather conditions rather than forest specific variables. The integration of the Copernicus dataset, coupled with the isolation of Ireland, ensures a comprehensive and tailored approach to forest fire risk assessment in the country.

**Explanation of Variables Related to Weather from CD's API:**

The CD's API dataset comprises various key variables related to weather, each playing a distinctive role in assessing fire danger levels and predicting fire behaviour. Here is a summary of the significant variables:

* Build-Up Index (Dimensionless): A weighted combination of the Duff Moisture Code and Drought Code, indicating the total fuel available for combustion. Often used for pre-suppression planning.
* Burning Index (Dimensionless): Measures the difficulty of controlling a fire, derived from the Spread component and Energy Release component.
* Danger Rating (Dimensionless): Equivalent to the Fire Weather Index (FWI), reduced to 6 classes of danger, providing a harmonized spatial distribution of fire danger levels.
* Drought Code (Dimensionless): Indicates moisture content in deep compact organic layers, representing a fuel layer at 10-20 cm deep.
* Drought Factor: Represents fuel availability, given as a number between 0 and 10, influenced by recent temperatures and rainfall events.
* Duff Moisture Code (Dimensionless): Indicates moisture content in loosely compacted organic layers of moderate depth, representative of the duff layer that is 5-10 cm deep.
* Energy Release Component (J/m2): Reflects the potential heat release per unit area in the flaming zone, providing guidance on fire intensity.
* Fine Fuel Moisture Code (Dimensionless): Indicates moisture content in litter and other cured fine fuels, with a scale ranging from 0-99.
* Fire Daily Severity Index (Dimensionless): Numeric rating of the difficulty of controlling fires, exponentially increasing as the Fire Weather Index rises.
* Fire Danger Index (Dimensionless): Metric related to the chances of a fire starting, its rate of spread, intensity, and difficulty of suppression.
* Fire Weather Index (Dimensionless): A combination of Initial Spread Index and Build-Up Index, indicating the potential frontal fire intensity.
* Ignition Component (%): Measures the probability a firebrand will require suppression action, expressed as a probability on a scale of 0 to 100.
* Initial Spread Index (Dimensionless): Combines the Fine Fuel Moisture Code and wind speed to indicate the expected rate of fire spread.
* Keetch-Byram Drought Index (Dimensionless): Represents cumulative moisture deficiency in deep duff and upper soil layers, providing insight into flammability.
* Spread Component (Dimensionless): Measures the theoretical ideal rate of fire spread, expressed as a dimensionless variable. Offers insight into fire spread dynamics, siding in fire behaviour prediction and management.

These variables collectively contribute to a comprehensive understanding of fire danger levels and behaviour, enabling effective fire risk assessment and management strategies.

## **3.1.2 Simulated CCF Forest Data Variables:**

The creation of simulated CCF forest data tailored to Irish forests was necessitated by the absence of real data specific to this forest type in Ireland. Given the unique characteristics of Irish CCF forests, including species diversity, canopy cover, and ecological conditions, exiting datasets were insufficient to capture the intricacies of fire risk dynamics. While alternative approaches such as using historical data or extrapolating from similar regions were considered, they lacked the specificity required for accurate modelling of Irish CCF forests. Despite inherent limitations in simulation models, the decision to create simulated CCF forest data was imperative to develop predictive models tailored precisely to Irish forest landscapes. The approach ensures a comprehensive understanding of fire dynamics, enabling more effective forest fire risk management strategies tailored to the Irish context.

* Overall Fire Risk (Numeric): Represents the comprehensive assessment of fire risk in the simulated CCF forest, derived from a combination of various contributing factors.
* Fine Fuel Moisture (Numeric): Indicates the moisture content in litter and other cured fine fuels, influencing the flammability of surface-level vegetation.
* Initial Spread Index (Numeric): Reflects the expected rate of fire spread based on the combination of fine fuel moisture and wind speed in the simulated CCF forest.
* Uneven-Aged Canopy (Binary): Indicates the presence or absence of an uneven-aged canopy structure, influencing the spatial distribution of vegetation and potential fire spread.
* Species Diversity (Numeric): Represents the variety of tree species within the simulated CCF forest, influencing overall ecosystem resilience and fire dynamics.
* Continuous Canopy Cover (Binary): Indicates whether the forest has continuous canopy cover, impacting fuel continuity and potential fire spread.
* Drought Conditions (Numeric): Reflects the simulated moisture deficiency in the forest, providing insights into the potential flammability of organic material in the ground.
* Wind Speed (Numeric): Represents the simulated wind speed within the forest environment, a critical factor influencing fire behaviour and spread.
* Temperature (Numeric): Indicates the simulated temperature conditions within the CCF forest, influencing overall fuel moisture and fire risk.
* Fire Warnings (Binary): Indicates whether there are simulated fire warnings in the CCF forest, providing information on potential fire risk events.
* Fire Occurrence (Binary): Indicates the occurrence or absence of simulated fires in the CCF forest, serving as a crucial outcome variable for assessing the accuracy of fire risk models.

These variables collectively contribute to a comprehensive understanding of fire risk dynamics in the simulated CCF forest. The combination of meteorological data from CD's API and these simulated forest-specific variables forms a robust foundation for developing accurate and effective machine learning models for forest fire risk assessment in Ireland.

## **3.2 Data Cleaning:**

Data cleaning is a critical process in the data preparation phase that focuses on enhancing the quality, accuracy, and reliability of a dataset. It involves various techniques to identify and rectify issues such as missing values, outliers, inconsistencies, and irrelevant information.  
Following techniques are applied for Data Cleaning:

**Handling Missing Values:**

Technique: Imputation or removal of missing values.

Description: Fill missing values using methods such as mean, median, or regression for numerical variables. Alternatively, remove records or variables with missing values.

**Outlier Detection and Treatment:**

Technique: Statistical methods (Z-score, IQR) for identifying outliers, and removal or transformation.

Description: Identify outliers using statistical measures and address them by either removing them or transforming them to minimize their impact.

**Consistency Check:**

Technique: Comparison of values against predefined rules or standards.

Description: Ensure consistency across variables by validating values against predefined criteria or rules.

**Normalization/Scaling:**

Technique: Min-Max scaling or Z-score normalization for numerical variables.

Description: Normalize numerical features to a similar scale, preventing features with larger magnitudes from dominating the analysis.

**Validation of Binary Variables:**

Technique: Validation to ensure binary variables only contain valid values (0 or 1).

Description: Confirm that binary variables adhere to the expected format, containing only valid values.

**Data Integration:**

Technique: Integration of datasets based on common identifiers (e.g., time periods, geographic locations).

Description: Combine datasets with common identifiers, creating a unified dataset for analysis.

**Data Type Check:**

Technique: Inspection and correction of data types for each variable.

Description: Confirm that variables are appropriately represented as numerical or categorical types.

**Data Duplicates:**

Technique: Identification and removal of duplicate records.

Description: Detect and remove duplicate records to eliminate redundancy in the dataset.

**Data Format Standardization:**

Technique: Standardizing date formats and other data representations.

Description: Ensure consistent data formats, such as date formats, to maintain uniformity across the dataset.

**Handling Irrelevant Variables:**

Technique: Removal of irrelevant or redundant variables.

Description: Eliminate variables that do not contribute significantly to the analysis, streamlining the dataset.

## **3.3 Label Encoding:**

In the label encoding section, the 'OverallFireRisk' column has undergone the following mapping:

Mapping for 'OverallFireRisk' column:

Extreme: 0

High: 1

Low: 2

Moderate: 3

Very Low: 4

This label encoding technique transforms categorical descriptors of fire danger levels into unique numerical labels. The assigned numeric values, ranging from 0 to 4, allow machine learning algorithms to comprehend and analyse the fire risk data effectively. This process enhances the readiness of the data for subsequent stages in the forest fire risk assessment, as machine learning models often require numerical representations for accurate training and prediction. Label encoding provides a streamlined approach to convert qualitative information into a format compatible with machine learning algorithms, contributing to the overall success of the forest fire risk assessment endeavour.

## **3.4 Handling Imbalanced Data:**

Dealing with Imbalanced Data in CCF Forest Fire Risk Assessment Model:

**Background:**

Imbalanced data occurs when certain classes in the target variable are underrepresented. In the context of CCF forest fire risk assessment, the target variable is 'OverallFireRisk,' which encompasses various levels of fire risk. The ‘OverallFireRisk’ variable was selected as the target variable for its alignment with the research objective of assessing fire rank in CCF forests. It offers a comprehensive representation of fire risk levels, ranging from’ Extreme’ to ‘Very Low’, facilitating proactive decision-making in forest management. The choice was also influenced by the availability of quality data, making it suitable for model development and validation.

**Imbalanced Class Distribution:**

'OverallFireRisk' exhibits an imbalanced distribution, where specific fire risk levels may have fewer instances compared to others. This imbalance can lead to challenges in model training, with the risk of the model being biased towards the majority class.

**Significance of Imbalanced Data Handling:**

Addressing the imbalanced class distribution is crucial to ensure that the machine learning model can effectively learn patterns and make accurate predictions for all fire risk levels. This is particularly important in scenarios where accurate identification of minority classes is essential for decision-making.

**Target Variable Overview:**

'OverallFireRisk' consists of categories representing diverse fire risk levels, such as 'Extreme,' 'High,' 'Moderate,' 'Low,' and 'Very Low.' Each category signifies a specific degree of fire risk associated with CCF forests.

**RandomOverSampler Technique:**

To tackle the imbalanced class distribution, the code incorporates the RandomOverSampler technique from the imbalanced-learn library. RandomOverSampler is an oversampling method designed to address the scarcity of instances in the minority class.

**Mechanism of RandomOverSampler:**

RandomOverSampler works by randomly duplicating instances of the minority class until a more balanced distribution is achieved. This process involves creating synthetic samples for the less frequent class, mitigating the impact of class imbalance during model training.

**Prevention of Biased Model Training:**

The primary goal of using RandomOverSampler is to prevent machine learning models from disproportionately favoring the majority class during training. This helps in creating a more equitable learning environment, ensuring that the model considers all fire risk levels.

**Enhanced Generalization:**

The application of RandomOverSampler enhances the model's ability to generalize across all classes of fire risk. This is crucial for achieving a well-rounded and unbiased prediction capability, especially when dealing with imbalanced datasets.

**Contribution to Improved Model Performance:**

The resulting balanced dataset, generated through RandomOverSampler, significantly contributes to improved model performance. It enables the model to provide more accurate predictions for all fire risk levels, thereby enhancing its overall reliability and effectiveness.

**Practical Relevance:**

In real-world scenarios, where imbalanced classes could have profound consequences, the use of RandomOverSampler ensures that the developed CCF forest fire risk assessment model is robust and capable of handling varying frequencies within the 'OverallFireRisk' variable.

## **3.5 Exploratory Data Analysis:**

Exploratory Data Analysis is a crucial phase in the data science pipeline, offering insights into the dataset's characteristics, relationships between variables, and patterns that can guide subsequent modelling decisions. In this context, the EDA process focuses on understanding the features and their impact on the target variable 'OverallFireRisk.'

## **3.5.1 Scatter Plots for Feature Analysis:**

Scatter plots are employed to visually inspect the relationship between various features and the target variable 'OverallFireRisk.' For each feature, a scatter plot is generated, with the x-axis representing the feature's values and the y-axis denoting the corresponding 'OverallFireRisk' levels. By examining these plots, trends, patterns, and potential outliers can be identified. This aids in understanding how individual features contribute to the variability in fire risk levels.

## **3.5.2 Visualization of Categorical Features:**

* Bar Graphs:

Categorical features, such as 'drtcode' and 'FireWarnings,' are visually explored using bar graphs. Bar graphs provide a clear representation of the distribution of 'OverallFireRisk' across distinct categories within each categorical feature. This enables the identification of any significant variations in fire risk levels associated with specific categories. See fig 7 & 8.

A bar graph with blue and black lines

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Figure 7 Bar Graph

A bar graph with blue squares

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Figure 8 Bar Graph

* Line Graphs:

Line graphs are utilized to illustrate the impact of categorical features on 'OverallFireRisk' over a continuous range. This visualization method helps uncover trends or patterns in fire risk variation concerning the values of categorical features. See fig 9.

A barcode with text on it

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Figure 9 Line Graph

## **3.6 Feature Engineering:**

In the feature engineering phase of this project, strategic decisions were made to enhance the quality and relevance of the dataset, 'balanced\_data,' for subsequent machine learning model training. The initial step involved a comprehensive analysis of the dataset's correlation matrix, utilizing the seaborn library to create informative heatmaps. This analysis aimed to identify inter-feature relationships and dependencies, guiding the selection of features for further refinement.

Upon assessing the correlation matrix, Several features were deemed redundant or exhibited high correlation with others, potentially introducing multicollinearity issues. To address this, specific features were identified for removal, including 'surface,' 'FireWarnings,' 'ffmcode,' 'fdsrte,' 'dufmcode,' 'fwinx,' 'Unnamed: 0,' 'time,' 'fdimrk,' 'drtcode,' 'FireOccurrence,' and 'fbupinx.' The removal of these features was executed to streamline the dataset, eliminating redundancies, and reducing the dimensionality of the feature space.

Following the feature selection and removal process, an updated correlation matrix was generated and visualized using a heatmap. This provided a visual representation of the refined feature relationships within the modified dataset. The correlation matrix showcased the impact of feature engineering on mitigating multicollinearity and optimizing the dataset for the subsequent machine learning tasks.

The culmination of these feature engineering efforts ensures that the 'balanced\_data' dataset is not only more computationally efficient but also poised to contribute meaningfully to the training of machine learning models for fire risk assessment. The judicious selection and refinement of features lay a solid foundation for improved model interpretability, generalization, and predictive accuracy.

A screenshot of a data analysis

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Figure 10 Correlation matrix

A screenshot of a computer screen

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Figure 11 Updated Correlation matrix

## **3.7 Data Scaling and Splitting:**

Data scaling ensures that the various features representing forests characteristics and environmental factors are appropriately standardised, preventing any single feature from disproportionately influencing the model’s training process . By bringing all features to a consistent scale, the model can actively learn from the data without being biased towards certain attributes. Moreover, splitting the dataset into distinct training and testing sets is essential for evaluating the models performance accurately. The training set, comprising historical data on forest attributes and fire occurrences, serves as the foundation for training the machine learning model. By exposing the model to past patterns and relationships, it can learn to predict fire risk levels based on relevant features. \the testing set remains unseen during model training and is solely reserved for assessing model the models predictive performance. The separation ensures an unbiased evaluation, mimicking real-world scenarios where the model encounter new data It hasn’t been trained on. Through testing on unseen data, the model’s ability to generalise and accurately predict fire risk levels in CCF forests can be thoroughly evaluated, thus providing valuable insights for forest management and wildfire prevention strategies.

## **3.7.1 Standard Scaling with StandardScaler:**

Standard scaling, or z-score normalization, is employed to bring numeric features to a standard scale with a mean of 0 and a standard deviation of 1. This is crucial when features have different units or scales, ensuring that each feature contributes equally to model training. The StandardScaler from the scikit-learn library is applied to achieve this normalization.

**Detailed Steps:**

* Import the StandardScaler from scikit-learn's preprocessing module.
* Identify the numeric features in the dataset that require scaling.
* Initialize an instance of the StandardScaler.
* Fit the scaler on the training data to compute the mean and standard deviation.
* Transform both the training and testing sets using the computed mean and standard deviation.

The scaling process ensures that the features are centred around zero, providing a standardized input for the machine learning models. This step is particularly important for algorithms sensitive to the scale of features, such as K-Nearest neighbours or Support Vector Machines .Additionally, standard scaling makes the coefficients of linear models directly comparable, enhancing model interpretability and ease of explanation.

## **3.7.2 Dataset Splitting into Training and Testing Sets:**

The dataset is divided into two subsets: the training set and the testing set. The training set is used to train the machine learning models, while the testing set is reserved for evaluating the models' performance on unseen data. The train\_test\_split function from scikit-learn is commonly used for this purpose.

**Detailed Steps:**

* Import the train\_test\_split function from scikit-learn's model\_selection module.
* Identify the features (X) and the target variable (Z) in the dataset.
* Specify the test\_size parameter to determine the proportion of data allocated to the testing set (commonly set to 0.2 for an 80-20 split).
* Set the random\_state parameter for reproducibility of results.
* Execute the train\_test\_split function to obtain the training and testing sets for both features and the target variable.

The resulting sets, namely X\_train, X\_test, Z\_train, and Z\_test, are ready for use in training and evaluating machine learning models. This separation ensures that the model is assessed on data it has never seen during the training phase, providing a reliable estimate of its generalization performance.

The choice of an 80-20 split is commonly used in machine learning practice. It strikes a balance between having sufficient data for model training and retaining a sizable portion for evaluation. Additionally, setting random state parameter ensures that the same split is obtained each time, promoting result reproducibility, which is essential or research integrity and validation.

By performing data scaling and splitting, the code establishes a robust foundation for subsequent model training, enhancing the models' ability to generalize to new, unseen data and improving the overall reliability of the machine learning pipeline.

## **3.8 Tools Used:**

* **CDS API**: Used for Scrapping the data, reliable source of real time and historical weather info.
* **Language:** Python, for its versatility, extensive libraries for data analysis and ML
* **Pandas:** Used for data manipulation and reading CSV files efficiently.
* **Scikit-learn:** Employed for label encoding, data scaling, dataset splitting, and implementing machine learning algorithms.
* **Imbalanced-learn:** Utilized for addressing class imbalance using RandomOverSampler.
* **Matplotlib and seaborn:** Used for data visualization, including scatter plots, bar graphs, line graphs, and heatmaps for better insights into data
* **GridSearchCV:** Applied for hyperparameter tuning of machine learning models, finding optimal model parameters for improved performance.
* **Front-end Development:** HTML CSS, employed for developing user interfaces nd visualisations to interact with the data and model outputs.
* **Back-end development:** Python Django, building backend infrastructure to support data processing, model deployment, and web application.

# **4 Implementation**

## **4.1 KNN Classification**

In KNN classification, the problem is formulated as a classification task aiming to predict the overall fire risk. K-Nearest Neighbour’s (KNN) is employed as a classification algorithm. The model calculates the distances between data points and predicts the target variable based on many k-nearest neighbours. This method is suitable for capturing local patterns and relationships within the dataset.

## **4.1.1 Explanation:**

The application of the K-Nearest neighbours (KNN) algorithm to the fire risk assessment dataset proved to be a strategic choice, emphasizing proximity-based classification. The initial step involved an exploration of hyperparameter tuning, leveraging GridSearchCV to systematically evaluate various combinations of hyperparameters. The parameters considered included the number of neighbours ('n\_neighbors'), the weighting strategy ('weights'), and the distance metric ('p'). This tuning aimed to identify the optimal configuration that maximizes the model's predictive accuracy.

Hyperparameter tuning is crucial as it helps fine-tune the algorithm's behavior, optimizing its performance on the specific dataset. The selection of the best hyperparameters, as determined by GridSearchCV, ensures that the KNN model is tailored to the unique characteristics of the fire risk assessment data.

To assess the model's generalization capabilities and mitigate overfitting concerns, a robust cross-validation strategy was employed. The cross\_val\_score function executed a 5-fold cross-validation, which involves splitting the dataset into five subsets, training the model on four subsets, and evaluating it on the fifth. This process was repeated five times, with each subset serving as the validation set exactly once. Cross-validation provides a more comprehensive evaluation of the model's performance across different subsets of the data, offering insights into its stability and consistency.

The hyperparameter-tuned KNN classifier demonstrated exceptional performance on the test set, achieving an accuracy of 100%. The precision, recall, and F1-score metrics, as presented in the classification report, all reached perfect scores, underscoring the model's ability to precisely predict fire risk categories. This outstanding performance validates the effectiveness of hyperparameter tuning and cross-validation, highlighting their significance in ensuring a well-optimized and robust KNN model for fire risk assessment.

## **4.1.2 Parameters Used**

Optimal number of neighbors are 3, 5, 7,9. The number of neighbors used in KNN is determined through hyperparameter tuning to find the optimal value that maximizes the model's accuracy. This process involves trying different values for the number of neighbors and evaluating the model's performance with each setting. The justification for selecting a specific number of neighbors is to strike a balance between model complexity and generalization.

* Fewer Neighbors (e.g., 3 or 5): Using a small number of neighbors can make the model sensitive to noise or outliers in the data. While it may capture local patterns well, it might also be influenced by individual data points, leading to overfitting.
* More Neighbors (e.g., 7 or 9): On the other hand, using a larger number of neighbors can lead to a smoother decision boundary, potentially improving the model's ability to generalize to unseen data. However, it might overlook local patterns and details in the data.

The optimal number of neighbors is often chosen based on cross-validated performance metrics, such as accuracy, to ensure that the model performs well on new, unseen data. The goal is to find a balance that minimizes both bias and variance, resulting in a KNN model that generalizes effectively to different instances in the dataset. The choice of the number of neighbors is data-dependent and may vary based on the characteristics of the dataset and the underlying patterns in the data.

## **4.2 X\_Gradient Boosting:**

Gradient Boosting is applied using the XGBoost algorithm, treating the task as a classification problem. XGBoost is an ensemble technique that combines weak learners to build a robust model. It iteratively builds decision trees and optimizes for both bias and variance, resulting in improved accuracy. The algorithm is trained to classify the fire risk into distinct categories based on the features provided.

## **4.2.1 Explanation:**

The application of XGBoost, an advanced implementation of gradient boosting, to the fire risk assessment dataset signifies a sophisticated modeling approach, leveraging the strengths of an ensemble technique. The process commenced with an intricate exploration of hyperparameter tuning, employing GridSearchCV to systematically evaluate a range of hyperparameter combinations. Key parameters under consideration included the number of trees ('n\_estimators'), maximum depth of the trees ('max\_depth'), learning rate ('learning\_rate'), and subsample ratio of training instances ('subsample'). This exhaustive search aimed to identify the most effective hyperparameter configuration for optimizing the model's accuracy.

## **4.2.2 Parameters:**

Hyperparameter tuning is imperative in the context of XGBoost due to its sensitivity to parameter values, and optimal settings can significantly impact the model's performance. The selected hyperparameters, derived from GridSearchCV, ensure the XGBoost model is tailored to the unique characteristics of the fire risk assessment dataset.

To comprehensively assess the model's generalization performance and robustness, a cross-validation strategy was implemented. Cross-validation, particularly the 5-fold approach in this case, provides a more nuanced evaluation of the model's consistency across various subsets of the data. This approach enhances the model's reliability and ensures it can generalize well to unseen data.

The hyperparameter-tuned XGBoost classifier demonstrated robust performance on the test set, achieving an accuracy of approximately 93.7%. The classification report further details precision, recall, and F1-score metrics, highlighting the model's ability to effectively classify fire risk categories. This successful application of hyperparameter tuning and cross-validation underscores their importance in refining and evaluating the XGBoost model, contributing to its effectiveness in predicting fire risk levels accurately.

## **4.3 Random Forest Classifier**

The Random Forest Classifier is utilized as an ensemble learning method to address the classification task. This technique creates multiple decision trees during training and outputs the mode of the classes (classification) or mean prediction (regression) of the individual trees. It is effective in handling complex relationships and reducing overfitting.

## **4.3.1 Explanation:**

The application of the Random Forest classifier to the fire risk assessment dataset represents a robust ensemble learning technique that leverages multiple decision trees to make accurate predictions. The initial step involved a meticulous exploration of hyperparameter tuning, employing GridSearchCV to systematically evaluate various hyperparameter combinations. Parameters such as the number of trees ('n\_estimators'), maximum depth of the trees ('max\_depth'), minimum samples required to split an internal node ('min\_samples\_split'), and minimum samples required to be a leaf node ('min\_samples\_leaf') were fine-tuned to identify the configuration that maximized the model's accuracy.

## **4.3.2 Parameters:**

The selected hyperparameters for the Random Forest classifier were determined through a process of hyperparameter tuning using GridSearchCV. Let's delve into the technical reasons behind why these specific hyperparameters were chosen over others:

**Number of Estimators (n\_estimators):**

Contribution: The parameter dictates the quantity of decision trees in the ensemble, impacting the model's overall robustness.

Justification: The grid search systematically explored various values for n\_estimators, ensuring an optimal balance between improved model stability and computational efficiency.

**Maximum Depth of the Trees (max\_depth):**

Contribution: Regulating the depth of individual trees mitigates the risk of overfitting, particularly as deeper trees can capture intricate patterns in the training data.

Justification: The grid search sought the ideal max\_depth by assessing its impact on the trade-off between capturing complex relationships and preventing overfitting.

**Minimum Samples Split (min\_samples\_split) and Minimum Samples Leaf (min\_samples\_leaf):**

Contribution: These parameters control node splitting and leaf formation, respectively, influencing the granularity of decision tree structures.

Justification: The grid search dynamically adjusted min\_samples\_split and min\_samples\_leaf to strike a balance, enabling the model to generalize effectively without overly specific splits tailored to the training set.

**Feature Subset Size (max\_features):**

Contribution: Randomly selecting a subset of features at each split introduces diversity among trees, reducing correlation and enhancing overall model performance.

Justification: The grid search meticulously determined the optimal max\_features, ensuring an effective compromise between diversity and predictive accuracy.

## **4.4 Decision Tree Classifier**

A Decision Tree Classifier is implemented to model the relationship between the features and the fire risk. Decision trees split the dataset based on the most significant attributes, creating a tree-like structure. The model makes predictions by traversing the tree from the root to a leaf node. It is a simple yet powerful algorithm for classification tasks.

## **4.4.1 Explanation:**

The application of the Decision Tree classifier to the fire risk assessment dataset represents a straightforward yet powerful approach to predictive modeling. The process commenced with a systematic exploration of hyperparameter tuning, utilizing GridSearchCV to evaluate a range of hyperparameter combinations. Key parameters considered for tuning included the maximum depth of the tree ('max\_depth'), the minimum number of samples required to split an internal node ('min\_samples\_split'), and the minimum number of samples required to be a leaf node ('min\_samples\_leaf'). This optimization process aimed to identify the configuration that maximizes the model's accuracy.

Hyperparameter tuning is critical in Decision Tree models to find the right balance between model complexity and overfitting. The selected hyperparameters, derived from the GridSearchCV process, ensure that the Decision Tree classifier is appropriately configured for the specific nuances of the fire risk assessment data.

To comprehensively evaluate the model's generalization capabilities and robustness, a cross-validation strategy was implemented. The 5-fold cross-validation approach allowed for a thorough examination of the model's consistency across different subsets of the data, providing insights into its stability and performance.

The hyperparameter-tuned Decision Tree classifier demonstrated moderate performance on the test set, achieving an accuracy of approximately 57.8%. The classification report further details precision, recall, and F1-score metrics, shedding light on the model's effectiveness in classifying fire risk categories. This application of hyperparameter tuning and cross-validation highlights their importance in refining and evaluating the Decision Tree model, contributing to its reliability and accuracy in predicting fire risk levels. However, it's worth noting that Decision Trees might struggle to capture complex relationships present in the data compared to more sophisticated ensemble methods.

## **4.4.2 Performance Note:**

The Decision Tree classifier, despite its simplicity and interpretability, may not perform as well as other classifiers like Random Forest or XGBoost in certain scenarios. Here are some reasons why the Decision Tree may not be performing well in this case:

**Overfitting:**

* Decision trees are prone to overfitting, especially when they are deep and capture noise in the training data.
* Overfitting occurs when the tree is too complex, capturing both the underlying patterns and the noise in the training data, leading to poor generalization to new, unseen data.

**Lack of Ensemble Effect:**

* Unlike ensemble methods such as Random Forest or XGBoost, a single decision tree may lack the robustness provided by aggregating multiple trees.
* Ensemble methods are designed to mitigate overfitting and improve overall performance by combining predictions from multiple weak learners.

**Limited Expressiveness:**

* Decision trees may struggle to capture complex relationships in the data when the relationships are not inherently hierarchical or when feature interactions are intricate.
* Other models like Random Forest or XGBoost can handle more sophisticated relationships.

**Sensitivity to Data Variations:**

* Decision trees are sensitive to variations in the training data, and slight changes in the dataset can result in different tree structures.
* This sensitivity can lead to instability in the model's performance.

**Insufficient Hyperparameter Tuning:**

The hyperparameters of the Decision Tree Classifier, such as the maximum depth and minimum samples split, might not have been fine-tuned adequately during the hyperparameter tuning process.

## **4.5 Support Vector Machine (SVM) Regression**

SVM Regression is applied to predict the area of land burnt. SVM looks for a hyperplane that best separates the data into different classes while considering outliers. The epsilon loss function is used for regression in high-dimensional space. Various kernels such as RBF, linear, polynomial, and sigmoid are explored to find the optimal hyperplane.

## **4.5.1 Explanation:**

The application of Support Vector Machines (SVM) to the fire risk assessment dataset demonstrates the versatility of this algorithm in handling both linear and non-linear classification tasks. The process commenced with an in-depth exploration of hyperparameter tuning, employing GridSearchCV to systematically evaluate various hyperparameter combinations. Key parameters considered for tuning included the regularization parameter ('C'), the kernel type ('linear', 'rbf', 'poly'), and the gamma parameter ('scale', 'auto'). This comprehensive search aimed to identify the optimal hyperparameter configuration that maximizes the model's accuracy.

Hyperparameter tuning is crucial in SVM models to find the right balance between model flexibility and regularization, ensuring optimal performance on the specific dataset. The selected hyperparameters, derived from the GridSearchCV process, tailor the SVM classifier to the unique characteristics of the fire risk assessment data.

To thoroughly assess the model's generalization capabilities and robustness, a cross-validation strategy was implemented. The 5-fold cross-validation approach facilitated a comprehensive evaluation of the model's consistency across various subsets of the data, enhancing its reliability and ability to generalize effectively. The hyperparameter-tuned SVM classifier demonstrated robust performance on the test set, achieving an accuracy of approximately 88.8%. The classification report further details precision, recall, and F1-score metrics, highlighting the model's effectiveness in accurately classifying fire risk categories. This successful application of hyperparameter tuning and cross-validation underscores their importance in refining and evaluating the SVM model, contributing to its reliability and accuracy in predicting fire risk levels. SVM's ability to handle non-linear relationships and high-dimensional data makes it a valuable tool in the context of fire risk assessments.

## **4.5.2 Parameters:**

The chosen hyperparameters for the Support Vector Machine (SVM) model are:

* **C**: 10
* **gamma**: 'scale'
* **kernel**: 'poly'

These hyperparameters contribute to the superior performance of the SVM model:

**C (Regularization Parameter):**

* C controls the trade-off between achieving a low training error and a low testing error.
* A smaller C emphasizes a smoother decision boundary, allowing for some misclassifications, while a larger C aims for a more accurate classification of each training point.
* The optimal value for C is often found through cross-validation. In the given grid, [0.1, 1, 10] represents a range of regularization strengths.

**Kernel:**

* The choice of the kernel function significantly impacts the SVM's ability to handle complex relationships in the data.
* 'Linear' kernel is suitable for linearly separable data, while 'rbf' (Radial Basis Function) and 'poly' (Polynomial) kernels can capture non-linear relationships.
* The grid ['linear', 'rbf', 'poly'] allows exploration of different kernel options.

**Gamma:**

* Gamma (γ) defines the influence of a single training example, affecting the shape of the decision boundary.
* 'Scale' uses 1 / (n\_features \* X.var()) as the gamma value, and 'auto' uses 1 / n\_features.
* Higher values of gamma lead to a more complex decision boundary, potentially causing overfitting.

# **5 Evaluations**

## **5.1 Model Evaluation for KNN Classification:**

**Evaluation Metrics:**

* Mean Absolute Error (MAE): Measures the average absolute errors between predicted and actual values.
* Mean Squared Error (MSE): Measures the average squared errors between predicted and actual values.
* R-squared: Indicates the proportion of the variance in the dependent variable that is predictable.

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Figure 12 Classification report KNN

**Cross-Validation:**

Cross-validation is performed to ensure the robustness of the KNN model.

Multiple folds are used to train and validate the model, preventing overfitting.

## **5.1.1 Model Performance**

Regarding whether the model is overfitting, based on the provided results:

* Both the training and testing accuracies are 1.0, indicating that the model achieves perfect accuracy on both datasets. The fact that both training and testing accuracies are 1.0 raises suspicion of overfitting. In a real-world scenario, achieving perfect accuracy on the testing set is uncommon and could be a sign that the model is too complex and fitting noise in the training data.
* The classification report also shows perfect precision, recall, and F1-score for all classes on the testing set. Perfect scores across all metrics in the classification report for the testing set further support the possibility of overfitting. In practical situations, a model should not perform flawlessly on all aspects, as it may indicate over-reliance on the training data's specifics.
* The training accuracy is also 1.0, suggesting that the model perfectly fits the training data. The training accuracy being 1.0 suggests that the model has memorized the training data. While high training accuracy is desirable, a perfect score might indicate overfitting, especially if the model struggles to generalize to new, unseen data.

Given these observations, there is a strong indication that the model might be overfitting. Overfitting occurs when the model captures noise or random fluctuations in the training data, leading to excessively complex decision boundaries that do not generalize well to unseen data. In this case, the model achieves perfect accuracy on both the training and testing sets, which raises suspicion of overfitting, especially in real-world scenarios where noise and variability are expected.

## **5.1.2 Visualizations:**

Visualizations include scatter plots comparing actual vs. predicted values.

Confusion metrics are visualized for different folds.

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Figure 13 Confusion Matrix KNN

## **5.2 Model Evaluation for XGBoost Classifier:**

## **5.2.1 Evaluation Metrics:**

Accuracy: The proportion of correctly classified instances.

Precision, Recall, F1-score: Metrics for assessing the performance of multi-class classification.

Hyperparameter Tuning:

GridSearchCV is used to find the best hyperparameters for the XGBoost Classifier.

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Figure 14 Classification report XG Boost

## **5.2.2 Visualizations:**

Confusion matrix heatmap: Provides a visual representation of model performance on different classes.

Bar graph comparing accuracy and other metrics.

A screenshot of a graph

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Figure 15 Confusion Matrix XG Boost

**Confusion matrix of X\_gradient\_boosting:**

* True Negatives (TN): 36 (in the second row, second column)
* False Positives (FP): 1 (in the first row, second column), 1 (in the third row, second column), 2 (in the fifth row, second column)
* False Negatives (FN): 1 (in the first row, fourth column), 3 (in the second row, fourth column), 1 (in the third row, fourth column), 2 (in the fifth row, fourth column)
* True Positives (TP): 37 (in the first row, first column), 36 (in the second row, first column), 36 (in the third row, third column), 44 (in the fourth row, third column), 40 (in the fifth row, fifth column)

## **5.3 Model Evaluation for Random Forest Classifier:**

## **5.3.1 Evaluation Metrics:**

Accuracy, Precision, Recall, F1-score: Standard metrics for classification evaluation.

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Figure 16 Classification report RFC

Hyperparameter Tuning:

GridSearchCV is employed to find optimal hyperparameters for the Random Forest model.

## **5.3.2 Visualization:**

Confusion matrix heatmap: Shows classification results for different classes.

Bar graph comparing accuracy and other metrics.

**A graph with numbers and squares

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Figure 17 Confusion Matrix RFC

## **5.4 Model Evaluation for Decision Tree Classifier:**

## **5.4.1 Evaluation Metrics:**

Accuracy, Precision, Recall, F1-score: Standard classification metrics.

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Figure 18 Classification report Decision Tree

Hyperparameter Tuning:

GridSearchCV is used to find the best hyperparameters for the Decision Tree model.

## **5.4.2 Visualization:**

Confusion matrix heatmap: Visualizes model performance on different classes.

Bar graph comparing accuracy and other metrics.

Figure 19 Confusion Matrix Decision Tree

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## **5.5 Model Evaluation for Support Vector Machine (SVM) Regression:**

## **5.5.1 Evaluation Metrics:**

Accuracy: Measures the proportion of correctly predicted instances.

R-squared: Indicates the proportion of variance in the target variable explained by the model.

A screenshot of a computer

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Figure 20 Classification report SVM

Hyperparameter Tuning:

GridSearchCV is employed to find the optimal hyperparameters for the SVM Regression model.

## **5.5.2 Visualization:**

Scatter plots comparing actual vs. predicted values.

Evaluation metrics visualized for different folds in cross-validation.

A screenshot of a graph

Description automatically generated

Figure 21 Classification matrix SVM

# **6 Results & Conclusions:**

A bar graph comparing the performance metrics (accuracy, precision, recall, F1-score) of all models is given in figure 22 .

## **6.1 Accuracy comparison difference**

To compare the accuracies of different models, we can observe the differences in accuracy percentages across various machine learning models used in the project ( figure 23):

1. KNN:

Accuracy: 100%

1. XGBoost Classifier:

Accuracy: 93.69%

1. Random Forest Classifier:

Accuracy: 87.86%

1. Decision Tree Classifier:

Accuracy: 56.80%

1. SVM (Support Vector Machine) Classifier:

Accuracy: 88.83%

These accuracy percentages represent the overall performance of each model on the testing data. The differences in accuracy can be analyzed to understand how well each model is making correct predictions. Higher accuracy values indicate better predictive performance.

## **6.2 Observations:**

* XGBoost Classifier achieves the highest accuracy among the models, suggesting superior predictive capabilities.
* Random Forest Classifier and SVM also demonstrate high accuracy, indicating robust performance.
* KNN has a good accuracy.
* Decision Tree Classifier, while decent, falls behind the ensemble models (XGBoost and Random Forest) and SVM in terms of accuracy.

These differences in accuracy can be attributed to the inherent characteristics and strengths of each algorithm. It's important to consider factors such as model complexity, ability to handle non-linear relationships, and sensitivity to hyperparameter tuning when interpreting these accuracy values.

Graphs for confusion matrices of classification models.

A graph of different models

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Figure 22 Overall Comparison

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Figure 23 Accuracy comparison Table

## **6.3 Model Selection for Deployment:**

While XGBoost exhibited superior accuracy in our analysis, KNN was strategically selected for the dashboard due to its simplicity, interpretability, and computational efficiency. As the dashboard targets stakeholders without technical expertise. , KNN’s transparent nature enhances trust and comprehension in the models predictions. KNN provides faster inference times, vital for real time applications or deployments with restricted computational resources. By prioritising interpretability, efficiency, and user friendliness, KNN closely aligns with the projects specific requirements and constraints, making it a better choice for the dashboard. While, XGBoost’s versatility makes it suitable for various aspects of fire risk assessment, including real time prediction, optimising fire response, early warning systems, assessing vulnerability and environmental impact assessments.

The model deployment diagram used for providing the overall web interaction is given in fig 25.

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Figure 24 Deployment Diagram

**Web Service:**

Explanation: The Web Service serves as the interface between the end user (browser or API client) and the machine learning model. It handles incoming requests, processes them, and communicates with the machine learning model to obtain predictions. This component is responsible for managing the flow of information between the user and the model.

**Machine Learning Model:**

Explanation: The Machine Learning Model is the core of the forest fire risk assessment system. It has been trained on relevant datasets to predict the risk of forest fires based on input features. These features could include weather conditions, terrain information, or other relevant parameters. The model processes incoming data from the web service and produces predictions for the likelihood of a forest fire occurring.

**Database:**

Explanation: The Database stores and manages the data required for the forest fire risk assessment. This can include historical weather data, simulated data, or any other relevant information needed for training and evaluation of the machine learning model. The model might also store and retrieve its configuration or hyperparameters from the database.

**End User (Browser or API Client):**

Explanation: The End User represents the individual or system interacting with the forest fire risk assessment application. This could be a person using a web browser to access a user interface or an external system making requests through an API. The end user provides input data (such as location, weather parameters) to the system and receives the corresponding risk assessment predictions.

**Browser or API Client:**

Explanation: The Browser or API Client is the tool used by the end user to interact with the web service. It can be a web browser for human users or an API client for automated systems. This component sends input data to the web service, receives predictions, and may display the results to the end user.

**Model Storage:**

Explanation: Model Storage is where the trained machine learning model is persisted. It could be a file storage system or a dedicated model repository. This ensures that the latest version of the model is accessible to the web service for making predictions. Storing the model separately allows for easy updates and version control.

**Deployment of KNN Model for CCF Forest Fire Risk Assessment Using Django:**

**1. Model Development:**

The machine learning model chosen for CCF forest fire risk assessment is the K-Nearest Neighbors (KNN) model. This model was trained using historical data with features relevant to CCF forests, weather conditions, and other environmental factors.

**2. Integration with Django:**

The integration with Django, a Python web framework, facilitated the development of a web application for deploying the KNN model.

**3. Frontend Development with Django Forms:**

The front-end interface was created using Django Forms, providing an intuitive and user-friendly way for end-users to input data related to CCF forests. The form captures relevant features required for the fire risk prediction.

**4. User Input Handling:**

Django manages user inputs, ensuring data integrity and preparing it for consumption by the KNN model. Data validation is implemented to guarantee that the input adheres to the expected format and range.

**5. Model Prediction Integration:**

Upon form submission, the Django application passes the entered data to the deployed KNN model for prediction. This step involves seamlessly integrating the model into the application's backend.

**6. Result Display to the User:**

The prediction generated by the KNN model is presented to the user through the Django web interface. The output can be in the form of a risk level (e.g., low, moderate, high) depending on the model output.

**7. Scalability and Accessibility:**

The Django application is designed to handle multiple users simultaneously, ensuring scalability. This enhances accessibility, allowing users to access and benefit from the model predictions concurrently.

**8. User Interaction and Iterative Input:**

Users can interact with the Django web application, providing different sets of data to obtain real-time predictions for various CCF forest scenarios. The iterative input capability enables users to explore diverse situations.

**9. User-Friendly Interface:**

The front end, built with Django templates, ensures a user-friendly experience. The interface guides users through the input process, making it straightforward for individuals with varying levels of technical expertise.

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## **6.4 Dashboard:**

A screenshot of a computer

Description automatically generated

Figure 25 Web App

## **6.5 Conclusion:**

In conclusion, this comprehensive analysis aimed to assess and compare the performance of various machine learning models for fire risk assessment using a dataset containing diverse features related to environmental factors. The models considered include K-Nearest neighbours (KNN), XGBoost, Random Forest, Decision Tree, and Support Vector Machines (SVM). Each model underwent rigorous hyperparameter tuning and evaluation through cross-validation to optimize performance. The KNN model exhibited outstanding accuracy, achieving a perfect score on the test set. However, its simplicity may limit its ability to capture complex relationships in the data.

XGBoost demonstrated robust performance, attaining an accuracy of approximately 93.7%, making it a robust choice. Random Forest, while achieving an accuracy of 87.9%, displayed reliable performance, especially in handling diverse datasets. The Decision Tree model, with an accuracy of 57.8%, highlighted moderate performance, indicating potential limitations in capturing intricate patterns within the data. Lastly, the SVM model performed well with an accuracy of 88.8%, showing adaptability to various kernel types and suitability for both linear and non-linear relationships.

Considering the overall performance, XGBoost emerges as the most promising model for fire risk assessment in this analysis. Its ability to handle complex relationships, robustness in diverse datasets, and high accuracy make it a compelling choice. However, the selection of the most suitable model may depend on specific requirements, computational resources, and interpretability preferences. It is advisable to consider the unique characteristics of the application domain and dataset when making the final model selection.

In summary, this analysis identifies XGBoost as the most promising model for fire risk assessment in CCF forests due to its ability to handle complex relationships and deliver high accuracy. However, the final model selection should account for specific requirements, computational resources, and interpretability preferences in CCF forest management. Overall, this research informs the development of a tailored fire risk assessment system for CF forests in Ireland, laying the groundwork for more effective and sustainable forest management practices to protect ecosystems and communities from wildfire.

## **6.6 Implications and Recommendations**

From a data science perspective, this analysis shows the efficacy of various machine learning models on fire risk assessment., with XGBoost emerging as the top performer due to its ability to handle complex relationships and achieve high accuracy. However limitations such as reliance on simulated data, geographic focus on Ireland, and interpretability challenges of advanced models like XGBoost constrain the studies generalizability and stakeholder understanding. To overcome these limitations future research should prioritise collecting real-time data for CCF forest, expanding the study scope to a European scale, and integrating remote sensing. Moreover, efforts should be made to develop a real-time fire risk alert system tailored to CCF forests and integrate machine learning models into established frameworks like EFFIS system are essential to enhance forest fire risk assessment and mitigation efforts. These endeavours aim to propel the field of fire risk forward, fostering more effective management practices to protect .sustainable forestry.

Wordcount:14929

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