ISTANBUL TECHNICAL UNIVERSITY ★ INFORMATICS INSTITUTE

EVALUATION OF THE FIRE POTENTIAL INDEX UTILIZING NUMERICAL WEATHER PREDICTION FIELDS AND REMOTE SENSING IMAGERY

M.Sc. THESIS

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Thesis Advisor: Dr. Ahmet Özgür DOĞRU

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ BİLİŞİM ENSTİTÜSÜ

FPI ORMAN YANGINI POTANSİYELİ İNDEKSİNİN SAYISAL HAVA TAHMİN MODELİ ALANLARI VE UZAKTAN ALGILAMA VERİSİ İLE HESAPLANMASI

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Ferat Çağlar, a M.Sc. student of ITU Informatics Institute student ID 706151020, successfully defended the thesis entitled "Evaluation of the Fire Potential Index Utilizing Weather Prediction Model Fields and Satellite Imagery", which he prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

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Date of Submission : 04.05.2018
Date of Defense : 07.06.2018

To my family,

FOREWORD

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ABBREVATIONS

AVHRR	: Advanced Very High Resolution Radiometer
CLC	: CORINE Land Cover
$C_6H_{10}O_5$	: Cellulose
CO_2	: Carbone dioxide
ECMWF	: European Center of Middle Range Weather Forecasts
EUMETSAT	: European Organization for the Exploitation of Meteorological Satellites
FAO	: The Food and Agriculture Organization
FPI	: Fire Potential Index
HDF5	: Hierarchical Data Format 5
H_2O	: Water
MEUS	: Meteorological Early Warning System
MGM	: General Directorate of Meteorology
MODIS	: Moderate Resolution Imaging Spectroradiometer
MSG SEVIRI	: Meteosat Second Generation Spinning Enhanced Visible and Infrared Imager
NCL	: The NCAR Command Language
NDVI	: Normalized Difference Vegetation Index
NDWI	:Normalized Difference Water Index
O_2	: Oxygen
OGM	: General Directorate of Forestry
SPEI	: Standardized Precipitation Evapotranspiration Index
SPI	: Standardized Precipitation Index
SPPS	: Statistical Package for Social Sciences
TUBITAK	: Scientific and Technological Research Council of Turkey
USGS	: United States Geological Survey
WMO	: World Meteorological Organization

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EVALUATION OF THE FIRE POTENTIAL INDEX UTILIZING NUMERICAL WEATHER PREDICTION FIELDS AND REMOTE SENSING IMAGERY

SUMMARY

Forests are communes of large scale ecological units where many types of vegetation classes, fungi, microorganisms, animals, zooids, and soil live interactively. They cover vast territories and able to modify climatic conditions of their habitat. They serve many products and functions, some of which are utilized without effort. Prominent functions of forest are forestry products, hydrological, climatic, erosion control, medicine, recreational and scientific. Serving such benefits caused them to be an attraction for human population and finally lead to deforestation.

It is estimated that national boundaries of Turkey had lost two third of forest assets since the end of ice age. Deforestation has many causes, but one of the most important one is forest fires. Climate change contributes to the increasing pressure over forested areas in many parts of the world and Turkey. Mediterranean countries are specifically more vulnerable to the increased chance of flammability in the forests.

Turkey tries to protect its woodlands in those circumstances. Enhanced firefighting methods and strategies caused a decrease in the burnt areas per year despite the fact that annual number of fire occurrences are increasing. Forested fields and vegetation mass has an increasing trend in the last century. This is partially a result of a decrease in the demand for wood as raw material, heat, and energy source.

Wildfires are a natural part ecological cycle and have a crucial role in the sustainability of forests. Primary functions of forest fires are dissolving organic biomass, maintain and preserve biodiversity, removing inorganic materials. Besides naturel role of forest fires in ecology, they also have detrimental effects. Those negative consequences might be listed as medical problems, increased carbon dioxide release into atmosphere, loss of habitat, increased vulnerability to erosion, and even fatalities. Due to serious consequences of wildfires they need to be investigated in order to better understand their dynamics, further effects, and avoided.

Forest firefighting requires vast resources, and information. Due to severity of forest fires and difficulty of extinguishing efforts, a disaster management approach has to be applied which requires not only response strategies but also mitigation, adaptation, and preparedness. Early warning systems should be established indicating flammability in forested regions.

Combustion occurs in the availability heat, oxygen, and fuel. Forest have a prevailing function of photosynthesis activity which turns carbon dioxide (CO_2) and water (H_2O) into cellulose ($C_6H_{10}O_5$). That substance is known as cellulose. In the presence of favorable conditions, stored energy in the bounds of cellulose reveals rapidly in the form of forest fires. Ignition might start due to natural or anthropogenic factors. Most frequent natural cause of ignition is lightning whereas anthropogenic factors vary like intent, accidents, and negligence. Role of accidents is the most dominant factor

igniting forests whereas natural causes play a smaller role in fire initiation. Ignition sources might vary regionally. Fuel characteristics are determined by type, age, layering, and season. Atmospheric conditions play a significant role presenting favorable conditions for fire. High temperatures, rainfall deficit, horizontal and upward velocity of air parcels contribute fire risk significantly. As causes and favorable conditions for fire events are well understood, scientists had many attempts to mimic fire potential. Hydrological circumstances, recent condition of atmospheric state, drought status, meteorological gauge readings, remote sensing data are used to estimate fire danger. Parameters chosen to signal fire potential might vary due to availability of data, regions specific dominancy of factors, and computation capability. Whichever method is selected for a fire potential index, it is expected to be easy to compute but still be able to produce reliable results.

Fire Potential Index was chosen to estimate fire danger in Turkey in the present study. This method utilizes remote sensing data to determine vegetation status, atmospheric variables of temperature and relative humidity to indicate fuel moisture content, and land use data to distinguish between vegetation classes which have varying fuel characteristics like live/dead fuel loads and more importantly distinctive extinction moisture levels. Parameters of greenness level, water abundance of materials, and vegetation classes were together evaluated to signal likelihood of fire occurrence in a specific location. Daily fire potential mappings had been produced in order to investigate skill of index. General Directorate of Turkey supplied recordings of fire events in 2016.

Model used in the current study was able to successfully simulate monthly deviation of fire risk. Correlation between monthly areal average of FPI score and number of forest fire occurrences was calculated. Findings revealed that FPI scores and number of fires were strongly correlated, $r = 0.93$, $p < .01$. Rapid changes of FPI scores in consecutive days were in a good agreement with changes in fire occurrences. Fire events were coupled with relevant FPI scores and it is found that FPI was unable to indicate some of the fire events. Specifically, coastal regions experienced lots of fire events when moderate or low fire risk was indicated. Whereas in some cases, inland regions were free of fire events when extreme risk level was indicated. Coastal domains have high population density; therefore more likelihood of ignition is present compared to areas with sparse population. FPI could seriously benefit from consideration of inputs to evaluate ignition chances. Coastal and inland regions are also in different climatic regions which leads modifications in vegetation. Therefore, fire vulnerability of species should be further investigated. Ecoregion specific adaptations to the FPI model would increase the chance of indicating fire risk more accurately.

FPI ORMAN YANGINI POTANSİYELİ İNDEKSİNİN SAYISAL HAVA TAHMİN MODELİ ALANLARI VE UZAKTAN ALGILAMA VERİSİ İLE HESAPLANMASI

ÖZET

Orman, birçok türde bitkinin, mantarın, mikroorganizmanın, hayvanın ve toprağın etkileşimli olarak yaşadığı büyük ölçekli ekolojik bir komündür. Geniş bölgeleri kapsamakta ve yaşam alanlarının iklim koşullarını değiştirebilmektedir. Bazıları çaba sarf edilmeden faydalanılan birçok ürün ve fonksiyonu insanlığa sunmaktadırlar. Ormanların öne çıkan başlıca işlevleri orman ürünleri, hidrolojik, iklimsel, erozyon kontrolü, tıp, eğlence ve bilime katkıdır. Bu gibi faydalar sunmaları onların insan nüfusu için bir cazibe olmasına ve nihayetinde seyrelmelerine ya da tamamen yok olmalarına neden olmaktadır. Türkiye'nin günümüzdeki ulusal sınırlarının kapsadığı alanda buzul çağının bitiminden bu yana orman varlıklarının üçte ikisini kaybettiği tahmin edilmektedir. Ormansızlaşma birçok nedenden kaynaklanmaktadır ancak en önemlilerinden biri orman yangınlarıdır. İklim değişikliği, dünyanın birçok yerinde ve Türkiye'de ormanlık alanlarında artan baskıya katkıda bulunur.

Akdeniz ülkeleri özellikle ormanlarda tutuşma olasılığının artmasına karşı daha savunmasızdır. Türkiye bu şartlar altında ormanlık bölgelerini korumaya çalışmaktadır. Gelişmiş yangın söndürme yöntemleri ve yangınla mücadele stratejileri, yıllık yangın olaylarının artmasına rağmen, yanan alanların azalmasını sağlamıştır. Ormanlık alanlar ve orman kütlesi son yüzyılda giderek artmaktadır. Bu kısmen hammadde, ısı ve enerji kaynağı olarak odun talebindeki azalmanın bir sonucudur.

Yangınlar doğal ekolojik döngünün bir parçasıdır ve ormanların sürdürülebilirliğinde çok önemli bir role sahiptir. Orman yangınlarının temel fonksiyonları organik biokütlenin çözülmesi, inorganik materyallerin uzaklaştırılması ve bioçeşitliliğin korunmasıdır. Orman yangınlarının ekolojideki doğal rolünün yanı sıra, zararlı etkileri de vardır. Bu olumsuz sonuçlar tıbbi problemler, atmosfere karbondioksit salınımı, yaşam alanı kaybı, erozyona karşı savunmasızlığın artması ve hatta ölümler olarak sıralanabilir. Orman yangınlarının ciddi sonuçlarından dolayı dinamiklerini, etkilerini daha iyi anlamak ve yangınlardan kaçınmak için araştırılmaları gerekir.

Orman yangınlarıyla mücadele, büyük kaynak ve bilgi birikimi gerektirir. Orman yangınlarının ciddiyeti ve yangın söndürme çabalarının zorluğu nedeniyle, sadece müdahale stratejilerini değil, aynı zamanda zarar azaltma, uyum ve ön hazırlık safhalarını da kapsayan bütüncül bir afet yönetimi yaklaşımı uygulanmalıdır. Bunun için de ormanlık bölgelerdeki yangın riskini öngören erken uyarı sistemleri kurulmalıdır. Yanma, aktivasyon enerjisi, oksijen ve yakıtta mevcudiyetinde meydana gelir. Ormanlar, CO_2 ve H_2O'yu $C_6H_{10}O_5$'e dönüştüren fotosentez reaksiyonunun sürekliliği vardır. Bu reaksiyon sonucu ortaya çıkan madde selüloz olarak bilinir. Elverişli koşulların mevcudiyetinde, selüloz kimyasal bağlarında depolanmış enerji, orman yangınları şeklinde hızla ortaya çıkar. Tutuşma doğal veya beşeri faktörlerden dolayı başlayabilir. En sık görülen doğal tutuşma nedeni yıldırımdır, oysa beşeri

faktörler kasıt, kaza ve ihmal olarak sıralanabilir. Kazalar orman yangınlarının ortaya çıkmasında en baskın faktördür, doğal nedenler ise yangının başlamasında daha az rol oynar. Ateşleme kaynakları bölgesel farklılık gösterebilir. Yakıt özellikleri, tip, yaş, katmanlaşma ve mevsime göre belirlenir. Atmosferik koşullar, yangın için elverişli koşulların ortaya çıkmasında önemli bir rol oynamaktadır. Yüksek sıcaklıklar, yağış noksanlığı, yatay ve yukarı yönlü hava parsellerinin hızı yangın riskini önemli ölçüde artırmaktadır.

Yangın olaylarının nedenleri ve elverişli koşulları iyi anlaşıldığı için, bilim adamlarının yangın potansiyelini benzeştirme konusunda birçok girişimde bulunmuşlardır. Hidrolojik koşullar, atmosferik şartlar, kuraklık derecesi, uzaktan algılama verileri yangın tehlikesini tahmin etmek için kullanılmıştır. Yangın potansiyelini işaret etmek için seçilen parametreler, veri mevcudiyeti, yangını tetikleyen faktörlerin bölgesel değişkenliği ve hesaplama olanakları nedeniyle değişebilir. Bir yangın potansiyeli indeksinden hesaplama kolaylığı ve güvenilir sonuçlar üretmesi beklenir.

Bu çalışmada Türkiye'deki yangın riskini tahmin etmek için Yangın Potansiyeli İndeksi (Fire Potential Index, FPI) seçilmiştir. Bu yöntemde ölü yakıt olarak anılan ölü bitki artıklarının nem içeriği miktarını belirlemek için sıcaklık ve nispi nem atmosferik değişkenleri kullanılır. Uzaktan algılama ürünleriyle elde edilen Normalize Farklar Bitki İndeksi (NDVI) değerlerinin ortalamalardan sapmalarında yeşillik seviyesi ve dolaylı olarak canlı yakıtlardan ölü yakıtlara ne kadar dönüşüm olduğu belirlenir. Ölü yakıt miktarı yangın ortaya çıkmasında önemli bir role sahiptir. Özellikle atmosferik nem değişine çok hızlı cevap veren 10 saatlik yakıtlar (yarıçapı 0,6-2,5 cm olan bitki kalıntıları, dal parçaları, kozalak vb.) yangınların başlaması ve yayılmasında anahtar rol oynarlar. Bu tür yakıtlardaki nem içeriğini belirlemek için alansal veri sağlayan Avrupa Orta Vadeli Hava Tahminleri Merkezi (ECMWF) sayısal hava tahmin model çıktılarından faydalanılmıştır. Canlı yakıtların ve yangında enerji salınımında çok daha büyük öneme sahip 1000 saatlik yakıtların nem değişimlerine tepkisi çok yavaştır ve modellenmesi çok daha güçtür. Ancak, bu yakıt türlerinin nem içeriği değişimleri benzer karakteristikler gösterdiğinden bu yakıt türlerinin durumunu belirlemek için ise yer sabit uydu gözlemlerinden elde edilen NDVI verileri kullanılmıştır. Ölü yakıtlardaki nem içeriği tükenme nem seviyesine yaklaştıkça ve yeşillik seviyesi azaldıkça yangın olasılığı arttığı kabul edilir. Bu tez çalışmasında indeks işlevselliğini araştırmak indeksin iyi sonuç verdiği veya zayıf yönlerini ortaya koyabilmek için günlük yangın potansiyeli çıktı Türkiye Genel Müdürlüğü 2016 yılına ait yangın kayıtları gerek görsel gerek istatistiksel olarak karşılaştırılmıştır.

Çalışmanın sonucunda, mevcut çalışmada kullanılan model, yangın riskinin aylık sapmasını başarılı bir şekilde temsil edebilmiştir. Sosyal Bilimler için İstatistik Paketi (Statistical Package for Social Sciences; SPSS) ile yapılan Pearson's korelasyon analizi ile, aylık ortalama FPI skoru ile orman yangınlarının sayısı arasındaki korelasyon hesaplanmıştır. Bulgular, FPI puanlarının ve yangın sayısının kuvvetle ilişkili olduğunu, $r = 0.93$, $p <.01$ olduğunu ortaya koymuştur. FPI puanlarının ardışık günlerdeki hızlı değişimleri, yangın olaylarının bölgesel görülme değişimiyle uyum içinde olduğu görülmüştür. Buna ek olarak, FPI skorları ve günlük yangın sayılarının arasındaki korelasyon, istatistiksel olarak anlamlı ve güçlü olarak bulunmuştur ($r = .74$, $p < .01$).

Genel olarak nem akılarının ulaşamadığı iç kesimler özellikle İç Anadolu ve Güney Doğu Anadolu Bölgelerinde indeks en yüksek skorları üretmiştir. Ancak bu bölgelerde yangının ortaya çıkmasında birincil etken olarak insan aktiviteleri daha az olduğundan yangınların daha az isabetle öngörülmesi durumu ortaya çıkmıştır. İstanbul ve Bursa gibi şehirlerdeki yüksek nüfus, iklim karakteristiklerinden daha baskın bir şekilde yangınların ortaya çıkmasına neden olurken; en yüksek yangın sayıları Antalya, İzmir, Hatay gibi sıcak, kurak ve yoğun yerleşimin olduğu yerlerde gözlenmiştir. Yangın olayları ilgili FPI puanlarıyla eşleştirilmiş ve FPI'nın bazı yangın olaylarının gözlendiği yer ve konumda düşük değerler üretebildiği anlaşılmıştır. Özellikle, kıyı bölgelerde, orta veya düşük yangın riski ortaya konmuşken çok sayıda yangın olayı yaşandığı görülmüştür. Bazı durumlarda da aşırı risk seviyesi belirtilen iç bölgelerde yangın gözlenmediği tespit edilmiştir. Kıyı bölgeleri yüksek nüfus yoğunluğuna sahiptir. Bu nedenle, seyrek nüfuslu iç bölgelere kıyasla daha fazla tutuşma olasılığı vardır. Gelecek araştırmalarda, FPI, tutuşma şansını belirlemek için girdilerin değerlendirilmesinden ciddi olarak faydalanabilir. Kıyı ve iç bölgeler aynı zamanda bitki örtüsünde modifikasyonlara yol açan farklı iklim bölgelerinde de bulunmaktadır. Bu nedenle, türlerin yangına dayanıklılığı farklılaşabilir. Gelecek araştırmaların planlanmasında bu faktörün göz önünde bulundurulması faydalı olacaktır. Daha ileriki araştırmalarda FPI modeline farklı iklim kuşaklarındaki bölgelere özel uyarlamalar, yangın riskini daha doğru gösterme becerisini arttırabilir.

Yürütülen bu tez çalışmasının, Türkiye genelini inceleyerek, operasyonel yangın potansiyeli değerlendirmesi yapan bilinen ilk çalışma olması açısından önem taşıdığı düşünülmektedir. Daha önceki çalışmalarda yangın riskinin yüksek olduğu Antalya ve Muğla gibi illerin incelenmesine ek olarak, bu araştırmada tüm Türkiye'nin incelenmiş olması sebebiyle çalışmadan elde edilen bilgilerin Türkiye orman koruma ve yangınla mücadele konusunda yol gösterici olabileceğine inanılmaktadır.

Özetle, FPI bitki durumundan yola çıkarak yangına oluşma ihtimalini başarıyla ortaya koymaktadır. FPI, insan aktiviteleri, ek meteorolojik parametreler (rüzgar, stabilite vb.) ile birlikte değerlendirilirse yangın riskini ortaya koymada çok önemli bir araç olacaktır.

1. INTRODUCTION

Forest is defined as an integrated form of life, consists of trees at various height structure and thickness, bushes, herbaceous plants, mosses, ferns, fungi, animals, insects, microorganisms, and soil. It establishes on spacious extends, and able to modify surrounding climate (Aytuğ, 1976).

As being one of the major resources of oxygen, forests have a vital role on protecting ecological wellbeing of earth (Alkhatib, 2014). It is well known fact that forests are one of the most significant renewable natural resources, and provide many contributions to all creatures in the earth. For instance, forests are considered to be the world's second largest sink of carbon dioxide following to oceans (World Wide Fund, 2017a).

It has been previously demonstrated that forests serve many benefits according to their functions. Those functions are listed in the study of Eraslan (1989) as;

1. Forestry products manufacture function
2. Hydrological functions
3. Erosion control function
4. Climatic function
5. Public health function
6. Protection of nature function
7. Aesthetical function
8. Recreational function
9. National defense function
10. Scientific function.

Due to increasing human population and their demand for forest products, services, and land, forests are under rising threat (Akay, Wing, Sivrikaya, & Sakar, 2012). According to report of World Wide Fund (2017b), 129 million hectares of forest in the world which is almost the same size of South Africa has been lost during the years between 1990 and 2015. Previous research has established that forest resources are mostly affected by forest fires all over the world, but particularly in Mediterranean countries such as Italy, France, Greece and Turkey as a result of characteristics of their climate (Demir, Kucukosmanoglu, Hasdemir, Ozturk, & Acar, 2009). Research has shown that average of 4 million hectares in the world and average of 550 thousand hectares in Mediterranean zone are affected by forest fires (Doğan, 2009). Velez (2002) has indicated that 10-hectares forest in average burns in each fire occasion in Mediterranean zone. It is further stated that forest areas in Turkey, particularly in Mediterranean coastline, are highly sensitive to fires (Akay, Wing, Sivrikaya, & Sakar, 2012).

Omi (2005) has emphasized that forest fires have a crucial role regarding to dissolving organic biomass and transformation of nutrients. Forest fires maintain and preserve biodiversity and productivity (FAO, 2007). Fires function in forest ecosystems by removing dead materials and detritus which are generally dangerous for human life as well as wildlife (Omi, 2005). Besides of advantages of fires, there are many negative consequences (e.g., increased health problems, loss of animals, erosion, increasing carbon dioxide concentrations in atmosphere) of forest fires for both environment and society (FAO, 2007; Sazak & Abdullah, 2009). More specifically, forest fires are known to be one of the major threats to the forest existence.

It has been shown that frequency of wildfires has increased due to co-occurrence of climatic and anthropogenic factors in the last decades, thus forest fires has become a major issue (Masellia, Romanellib, Bottaib, & Zipoli, 2003). In this regard, it appears that any investigation for determination of fire risk and providing risk analysis method, especially in a fire-sensitive country like Turkey, would make great contribution to existing knowledge.

Since there are severe consequences of forest fires, they need to be dealt with a perspective of disaster management which covers four phases: mitigation, preparedness, response, and recovery. Preparedness phase of disaster management which includes determination of fire risk and issue early warnings is a crucial step for prevention of possible forest fires or minimizing unfortunate consequences of these fires.

A well-established forest fire potential estimating system should consider each element related to the fire triangle which is a conceptual model that evaluates fire presence by the driving parameters of oxygen, activation energy and fuel abundance. In order to accomplish this goal, scientists have developed indexes simulating fire risk. Nevertheless, instead of a complete fire triangle evaluation, most of those indexes rely on deviation of hydrological variables and some of them meteorological or vegetation parameters. This situation is a result of limited data availability, variability of deterministic parameters on a specific location, and computation capabilities. Indexes are meant to be practical which means they should be easy to compute but still be able to produce reliable results.

1.1 Purpose of the Thesis

The primary purpose of the present study is to investigate skill of Fire Potential Index (FPI) which was developed by Burgan and his colleagues in 1998. This index is an attempt to indicate fire risk at forests by assessing weather station readings, mappings of vegetation describing fuel characteristics and greenness level of plants derived by remote sensing. Burgan, Klever and Klever (1998)'s initial study on FPI utilized United States Geological Survey (USGS) vegetation maps, rain and temperature gauges, and Advanced Very High Resolution Radiometer (AVHRR) imagery in order to demonstrate risk of forest fires in the United States of America for years 1990-1994.

Similarly, in the present study, FPI model will be evaluated as Burgan, Klever and Klever (1998)'s formulation, but as data source Meteosat Second Generation Spinning Enhanced Visible and Infrared Imager (MSG SEVIRI) will be replaced with AVHRR instrument. CORINE 2012 land use data will replace fuel model map of United States National Fire Danger Rating System. Furthermore, instead of gauge readings European Center of Middle Range Weather Forecasts (ECMWF) numerical weather prediction model analysis data will be used. If the analysis fields of ECMWF are found to be worthy of determining fire potential, then forecast data could be used for prognosis of fire risk. FPI will be calculated for the year of 2016 on a daily basis covering complete national boundaries of Republic of Turkey.

Forest fire recordings of 2016 in Turkey will also be assessed in order to exhibit the skill of the fire risk mapping model. Success of the method will be presented by correlation statistics and by subjective verification by creation of overlay of FPI score and fire event maps.

2. LITERATURE REVIEW

Forest fires are known to be very significant multidimensional risk factor for ecosystems, society and economy (Arvai et al., 2008; Sazak & Abdullah, 2009). There are several negative consequences of forest fires, especially of wildfires on humans and animals (Sazak & Abdullah, 2009). For instance, forest can threaten human existence and their living conditions (Arvai et al, 2008). Loss of forest land also causes air pollution which in turn leads to development of health problems. Moreover, animals can need to migrate or even die as a result of losing their own habitats. Another negative effect of forest fires is decreased tree cover and associated rise of greenhouse gas emission (Sazak & Abdullah, 2009).

2.1 Causes of Forest Fires

Forests transform electromagnetic radiation emitted from the sun into chemical energy by photosynthesis (Omi, 2005). This transformation is slow but prevailing, therefore vast amounts of energy is accumulated in the forests due to long lifespan of trees. As soon as favorable conditions appear, stored energy in vegetation reveals rapidly in the form of wildfires, causing devastating environmental, socio-economical affects, and sometimes casualties. Due to serious consequences of fire events, their nature needed to be investigated. This includes producing fire risk maps to take action on mitigation strategies, locate firefighting stations for preparedness and issue early warnings for response stage of emergency management cycle.

Although forest fires spread rapidly and seem to appear out of nowhere, principals of fire are simple and well understood. Fire arouses in the availability of oxygen (O_2), fuel, and activation energy. That basic modeling approach is called fire triangle (Omi, 2005). In the case of wildfires oxygen is reckoned as freely available and abundance is virtually unlimited. However, availability of O_2 changes inversely along with the altitude. Wind speed contributes growth and spread rate of wildfires by increasing the amount of oxygen supplied into it. Vertical composition of atmosphere might also limit O_2 availability. Downward motions which are most likely when the area is under influence of high pressure systems could suffocate fires by resisting the rise of carbon dioxide (CO_2) and other waste gases. Atmospheric stability plays a key role in the development of fire events. Current and recent meteorological parameters such as days without precipitation, temperature, humidity, sunshine duration alter fuel condition significantly. Fuel type is also essential while determining fire risk. Some vegetation types are more sensitive to fire events because of their diameter, water retention value, leaf area etc...

2.2 Fire Risk Indexes

According to Food and Agricultural Organization (FAO)'s terminology (FAO, 1986), forest fire risk is "the chance of a fire starting as determined by the presence and activity of any causative agent". Given important negative effects on all creatures in earth and ecosystem, determination of fire risk is believed to be a first-line intervention in order to prevent fires and its consequences.

López, San-Miguel-Ayanz, and Burgan (2002) have indicated that there are fire risk indicators which have been used for a long time in order to eliminate forest fires and fighting against fires. The fire risk severity is mainly estimated with the help of indicator parameters which are likely to influence fire initiation and integration of these variables into an index (FAO, 1986)

Fire risk indexes have been used since regular meteorological observations are available. Wayne Palmer introduced Palmer Drought Index (Palmer, 1965) using precipitation, temperature and available soil water content. Drought status was utilized to estimate fire risk. Similar approach applied to mean annual precipitation, wet/dry bulb temperature and past 24 hour rainfall data in Keetch-Byram Drought index (Keetch & Byram, 1968) to estimate fire danger. That index was useful in anticipating not only the fire risk but also what types of fuel might contribute to the fire event. Formulation of this index or approach used as a part of some other indexes to determine fuel availability factor. For instance, Scott L. Goodrich imported this method into Fosberg Fire Weather Index (Goodrich, 2002) in order to predict fire potential using drought status, max temperature, and wind speed factors. With a different perspective instead of hydrological state, atmospheric circumstances were also assessed to signal fire likelihood. Degree of atmospheric stability was used to determine potential for a large fire by Davis Stability Index (Davis, 1969), and Haines Index (Haines, 1988).

Standardized Precipitation Index (SPI) is one of the most commonly used drought index and it is the suggested tool to monitor drought status by World Meteorological Organization (WMO) (Hayes, Svoboda, Wall, & Widhalm, 2011). An enhanced version of this index is Standardized Precipitation Evapotranspiration Index (SPEI) which take heed of temperature as well, was tested to predict seasonal burned area with ECMWF long term forecast data in Spain (Marcos, Turco, Bedía, Llasat, & Provenzale, 2015). Results showed that SPEI is a useful method to estimate seasonal burned area and incorporation of ECMWF data enhanced outputs compared to utilization of climatology (Marcos et. al, 2015).

Turkey also has an operational fire danger indication system called Meteorological Early Warning System (MEUS) which incorporates three day meteorological forecasts of temperature, relative humidity, wind speed and wind direction provided by ECMWF and aspect. This system is developed with the corporate effort of The Scientific and Technological Research Council of Turkey (TUBITAK), Bilkent University, General Directorate of Meteorology (MGM), General Directorate of Forestry (OGM) (General Directorate of Meteorology, 2017).

A more holistic method involving integration of fuel data types and fuel characteristics into a fire danger rating system was established in Fire Potential Index (FPI) (Burgan, Klaver, & Klaver, 1998). Both meteorological data and satellite imagery derived fuel maps and vegetation status taken into consideration in the FPI. This index was utilized by National Fire Danger Rating System in the United States of America. Same approach with variations in data sources and study area is applied by Lopez et al. (2002) in Europe. Laneve and Cadau (2007) also computed the index for Mediterranean countries obtaining promising results suggesting fire risk realistically.

Study at hand follows footprints of the method known as FPI (Burgan, Klaver, & Klaver, 1998) differentiating in data sources and study area. Instead of AVHRR imagery this study utilizes MSG SEVIRI satellite imagery in order to assess vegetation health, deterministic atmospheric model outputs by ECMWF are chosen instead of actual station observations, CORINE Land Cover Data replaced USGS Land Cover Classification data. Fire Potential Index is evaluated for complete coverage of Turkey where data is available and fire risk exists due to land cover class properties.

2.3 Forest Assets of Turkey

Turkey has a rich ecological diversity by having land of 78 million hectares, and forests have a significant place within this land. Almost all of the forests in Turkey are administrated by the General Directorate of Forestry, therefore our knowledge regarding to forest assets and forest fires are based on data and information provided by them.

One of the earliest development plans for forestry was made in 1917 in Turkey. After the year of 1963 these plans were revised in approximately 10 year cycles. The Official Gazette, as Turkey's governmental organ that announces regulations and laws, published Forest Management Regulation in 5th of February in 2008. According to this regulation's 4th clause in section one, principles of forest management are sustainability, economics, productivity, multi-purpose utilization, preservation of socio-cultural traditions, inter-sectoral coordination, global responsibility, conservation of biodiversity, conservation of aesthetics, carbon balance, participatory approach, and management objectives determined by the forest owner and techniques that made these goals possible (Forest Management Regulation, 2008).

Research by Yücel and Babuş (2005) shows that forested land of Anatolia was approximately 72% 12000 years ago, whereas this ratio significantly dropped down and became 22%. Today's forest coverage corresponds to the one third of historical situation. According to data derived from General Directorate of Forestry, in 2015, 28,6% of land of Turkey consisted of forests. It has been reported that out of forests in Turkey, 24% of them are in Black Sea Region, 20% of them are in Mediterranean Region, 18% of them are in Aegean Region, %15 of them are in Marmara Region, 11% of them are in Central Anatolia Region, 8% of them are in Eastern Anatolia Region, and 4% of them are in Southeastern Anatolia Region (Küçükosmanoğlu, 2012).

As seen in the Figure 1.1 taken from General Directorate of Forestry (2017), forestland of Turkey has risen about 2,1 million hectares in the 42-years period. Although increasing population and climate change pose a suppressing state of affairs on their existence usage of wood for heating, energy production and, industrial purposes significantly decreased in the last decades. Most of the population migrated from rural areas to urban areas. Released pressure on natural areas caused forests to boost in particular landscapes.

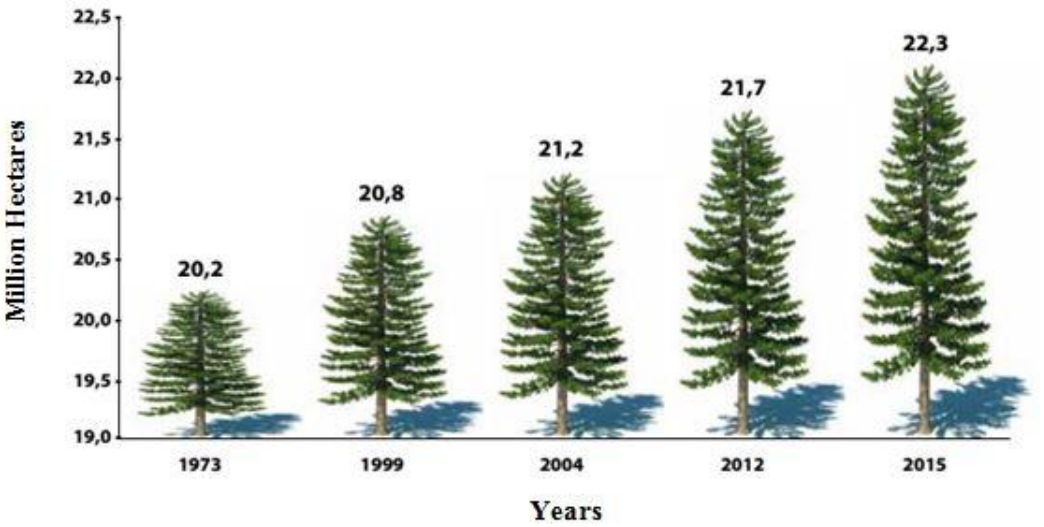

Figure 1.1 Change of forest assets of Turkey (General Directorate of Forestry, 2017).

2.4 Forest Fires in Turkey

Turkey suffers from forest fires notably like its neighbor countries settled at the shores of Mediterranean Sea. Forest fires occurred in Mediterranean basin are mostly driven by climatic characteristics (FAO, 2007). Extended summer season with very limited or no rainfall accompanied with daily average temperatures exceeding 30 ˚C lead reduction of moisture content of forest litter layer down below 5%. Fire hazard is also affected by wind. Inland winds with low humidity and high speeds increase evapotranspiration significantly. Those are favorable conditions for forest fire, and thus any contribution to heat (natural or anthropogenic) can result in destructive conflagration (FAO, 2007).

Due to complex topography and being under influence of four different high and low pressure systems meteorological conditions vary quickly and strongly both temporally and spatially. High variability in atmospheric state extends the span of active fire season and sometimes fires occur way outside of warm season and even in the middle of winter. High variability in climate conditions also cause variations in vegetation and vulnerability to fire incidents. Those situations make fire defense more challenging for Turkey. Therefore, a more scientific and systematic approach is required in order to monitor and forecast wildfire occurrences.

Literature has demonstrated that there are two main world-wide reasons for forest fires:

lightening and anthropogenic (Küçükosmanoğlu, 1985). As in the rest of the world, forest fires in Turkey are generally result of lightening and humans. However, it is important to mention here that humans cause fires much more than lightening (Küçükosmanoğlu, 2012). When forest fires are investigated for their sources, it is possible to divide human induced fires into five main categories. These are carelessness and neglect, accident, intention, unknown and lightening in Turkey (Kurt, 2014).

It has been indicated that almost 60% of Turkey's forest area is considered to be fire sensitive (San-Miguel-Ayanz et al., 2017). In Turkey, the first forestry law was introduced in 1937, thus our knowledge about forest fire statistics are limited to years after 1937. 1.662.033 hectares of forest area has been damaged in total of 101.088 forest fire occasions between years of 1937 and 2016 in Turkey (Avcı & Boz, 2017). Figure 1.2 represents amount of burnt areas and number of fires between the years of 1988 and 2016 based on the fire recordings compiled by General Directorate of Forestry (2017).

As historical fire events of Turkey from 1988 to 2016 are examined, it is clear that there is an increase in fire likelihood. Figure 1.3 shows a steady increase in total number of annual fires with some deviation due to climatic conditions, whereas burnt area per fire (see Figure 1.2) values slowly decreases except for the years in which severe drought conditions were experienced. This is a result of enhanced firefighting methods and, strategies, especially utilization of firefighting aircrafts.

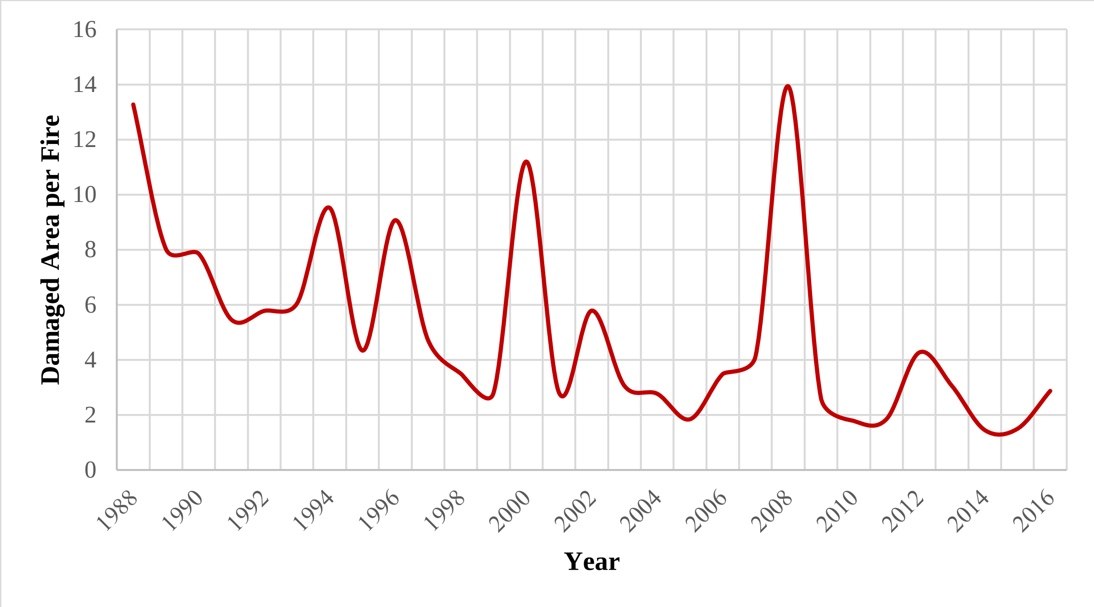

Figure 1.2 Amount of burnt area per fire occasion.

Figure 1.3 further represents amount of burnt areas and number of fires between the years of 1988 and 2016 based on the fire recordings provided by General Directorate of Forestry (2017). It might be also worth to mention here that in terms of burnt area, in Turkey, fires bigger than 500 hectares are considered to be "great fire" (Küçükosmanoğlu, 1986).

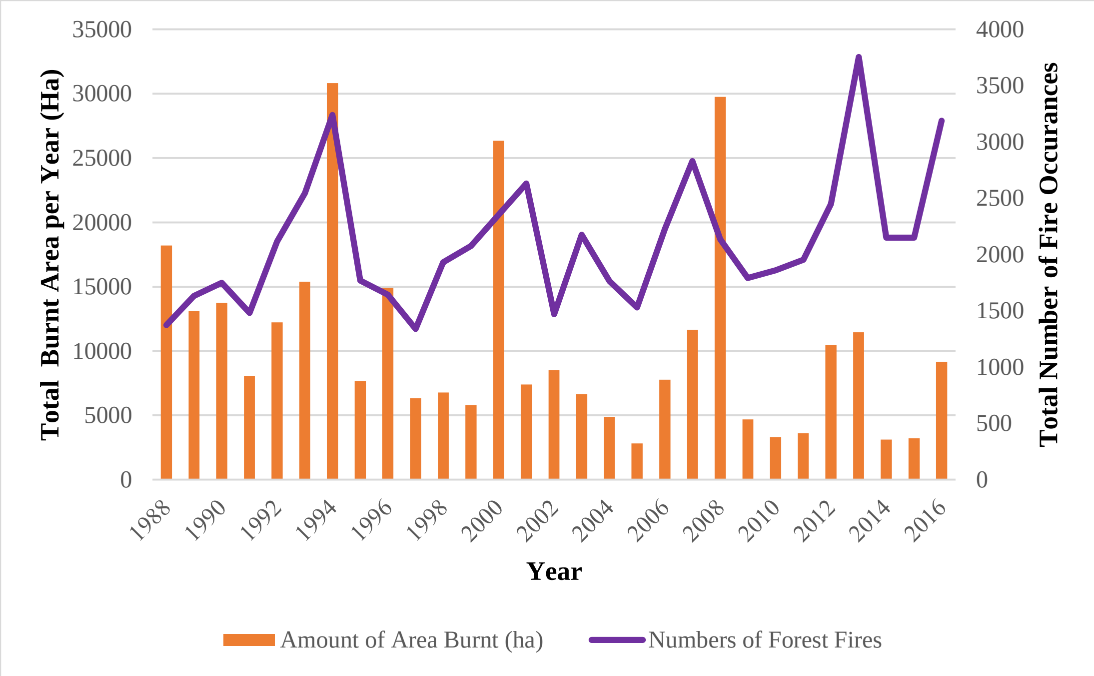

Figure 1.3 Amount of burnt area and numbers of fires.

According to Forest Fires in Europe, Middle East and North Africa report of European Commission, Turkey takes the 8th place for the number of fires and burnt areas among 28 countries based on data from 2016 (San-Miguel-Ayanz et al., 2017).

Fire risk increases rapidly at noon while there is less chance of fire occurrence during other times of the day as can be seen in Figure 1.4.

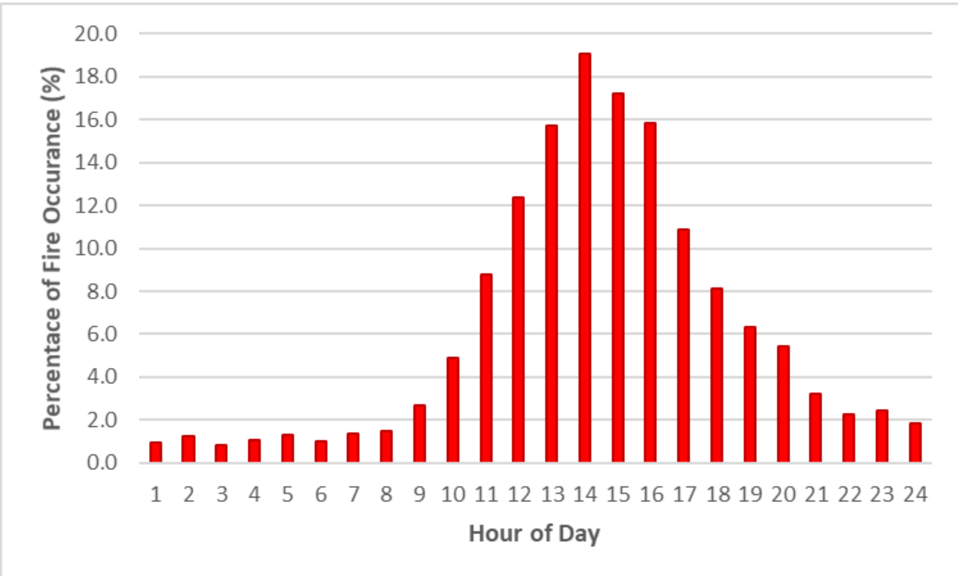

Figure 1.4 Diurnal change of fire occurances in 2016.

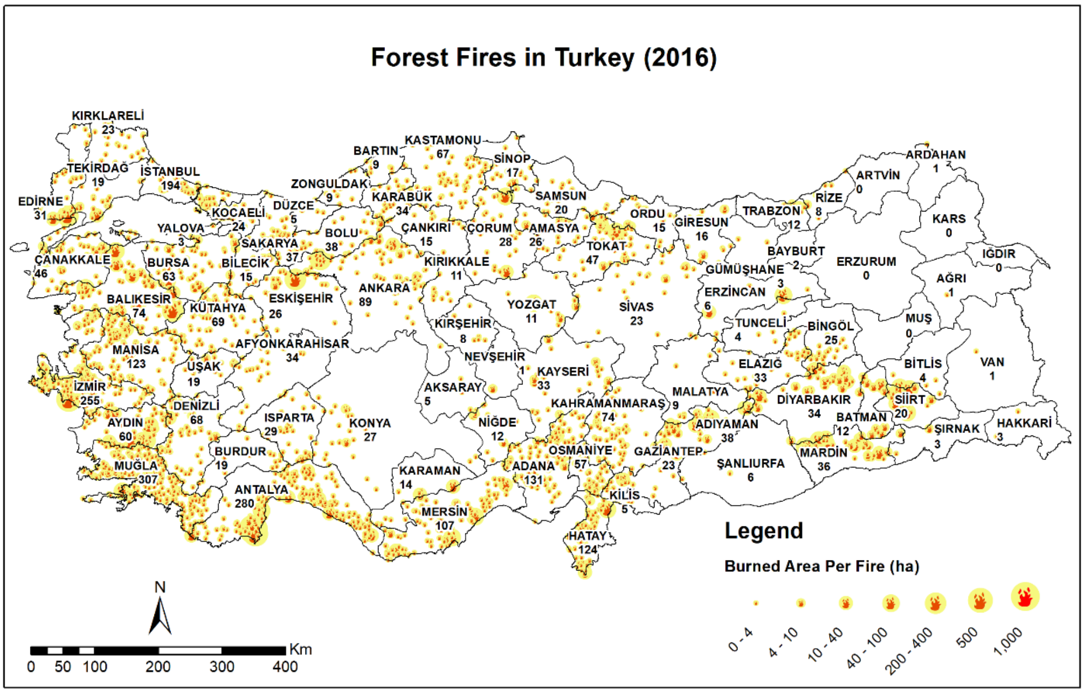

Figure 1.5 Forest firest in Turkey (2016).

Spatial distribution of forest fires in Turkey in the year of 2016 are visualized and number of fires in provincial boundaries are mapped in Figure 1.5. Map shows that all the forested areas are vulnerable to fire but particularly southern parts face a greater risk in Turkey. This proves that climatology is a significant driver while determining fire risk. Istanbul (the most populated city of Turkey) seems to be an exception to this where the number of forest fires are dramatically different than the surrounding provinces. Artificial causes also have an important role while determining fire risk, since densely populated cities have higher number of fire occurrences than the nearby cities which are located in similar climate ecoregions.

2.5 Causes of Forest Fires in Turkey in 2016

Data taken from General Directory of Forestry (2017) revealed that total of 9156.3 hectares of forest burnt in 2016. Percentages of burnt areas based on the causes of fires are represented in the Figure 1.6

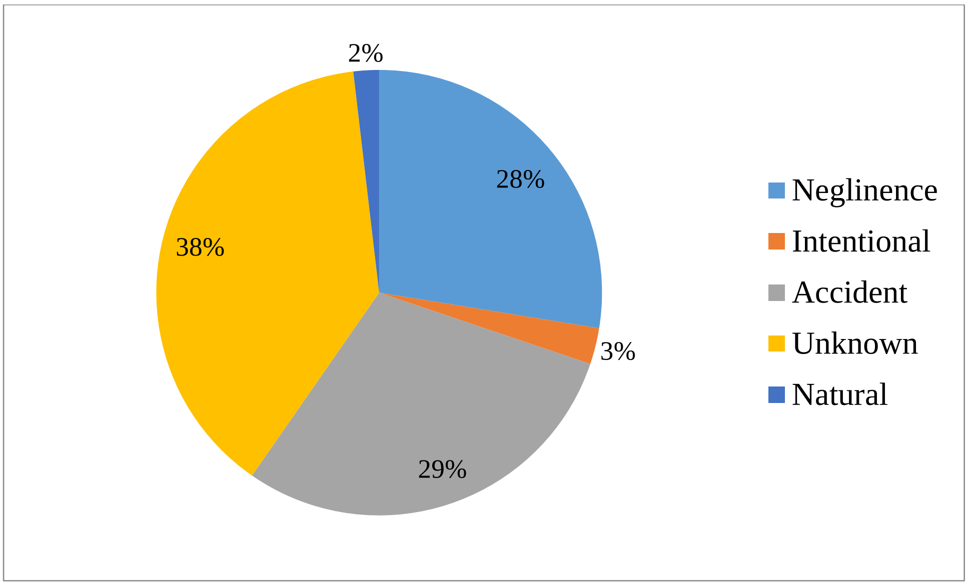

Figure 1.6 Percentages of burnt area based on fire cause.

As seen in the Figure 1.6, negligence, accident, and unknown reasons have the highest percentages whereas natural and intentional reasons have the lowest percentages. Table 1.1 further shows total burnt area in hectares based on main causes and secondary causes of forest fires.

Table 1.1 Burnt area based on main and secondary causes of forest fire.

Main Cause	Secondary Cause	Burnt Area	Total
Neglience	Stubble fire	1027.3	2523.2
	Dump	84.2	
	Hunting	11.4	
	Shepherd fire	87.7	
	Cigarette	175.2	
	Picnic	156.9	
	Other	980.5	
Inten-tional	Terror	82.4	240.5
	Incension	69.9	
	Expand	17.8	
	Other	70.4	
Accident	Traffic	8.9	2699.2
	Energy	2209.5	
	Other	480.8	
Unknown		3523.6	3523.6
Natural		169.8	169.8

3. METHOD

A realistic fire emulation should assess all decisive parameters of a fire incident. Fundamentals of combustion are given in fire triangle which is presented in Figure 3.1 and fuel related interactions which are assessed in FPI are further visualized in Figure 3.2.

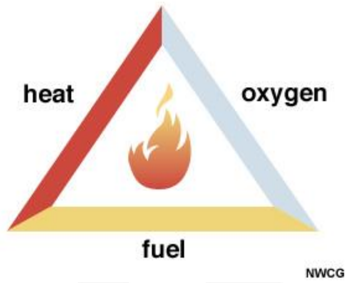

Figure 3.1 Fire triangle model (Url-1).

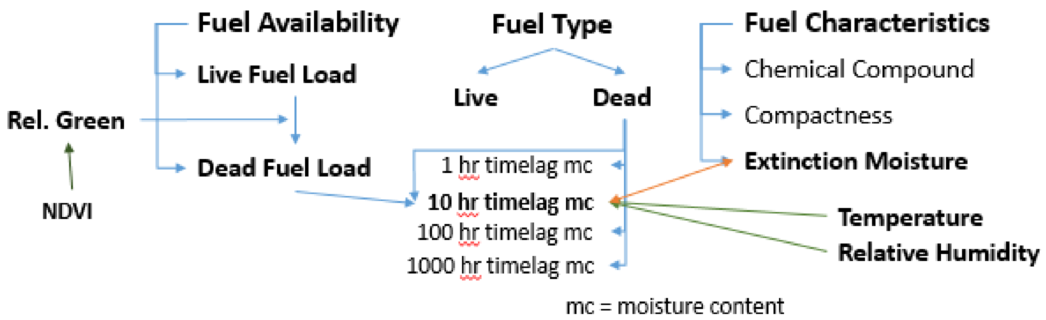

Figure 3.2 Fire risk evaluation of FPI due to fuel characteristics and environmental drivers.

In the field of fire management, fuel component of fire triangle is classified based on burning characteristics since it gives an easier approximation of fire behavior to firefighters in the field and fire experts who are trying to understand and model fire evaluation.

Fuels are mainly divided into two types: live and dead fuels. Live fuels are able to access water actively by their roots therefore their moisture content are less dependent to atmospheric state. However, dead fuels are more open to influences of current and recent weather conditions. The most descriptive characteristic of fuels in fire potential examination is the time needed to pass from initial moisture content to equilibrium moisture content. This change is illustrated in Figure 3.3.

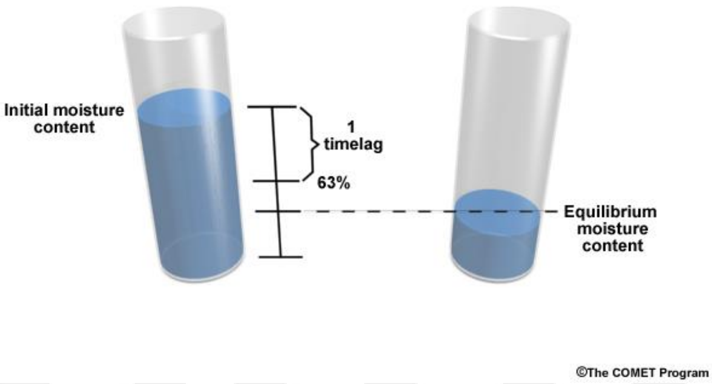

Figure 3.3 Illustration of fuel moisture change (Url-2).

Pace of the change is mostly determined and parameterized by diameter of fuels. Dead fuels are divided into classes like: 1, 10, 100, 1000 hour timelag fuels (Deeming, Burgan, & Cohen, 1977).

a) 0 – 0.6 cm diameter fuels are called 1-hour timelag fuels.
b) 0.6 – 2.5 cm diameter fuels are called 10-hour timelag fuels.
c) 2.5 – 7.7 cm diameter fuels are called 100-hour timelag fuels.
d) 7.7 – 20.5 cm diameter fuels are called 1000-hour timelag fuels.

FPI model accepts that abundance and water content of 10-hour timelag fuels are the most important parameters in order to successfully indicate fire occurrence. Ten-hour timelag fuels are called that way due to their water holding capabilities. A typical ten-hour timelag fuel might lose the moisture within in 10 hours from 100 % to the equilibrium moisture content. Their significance on determining fire risk is due to their coverage on forest floor. Their abundance increases the risk of fire propagation through the ground which is the usual scenario of a developing fire event. Since abundance of ten-hour timelag fuels on flammability is significant, level of their existence in a fire susceptible area is needed to be found. Generation of fuel related fields are descripted in detail in section 3.1.3. Different timelag fuel classes can be seen in Figure 3.4.

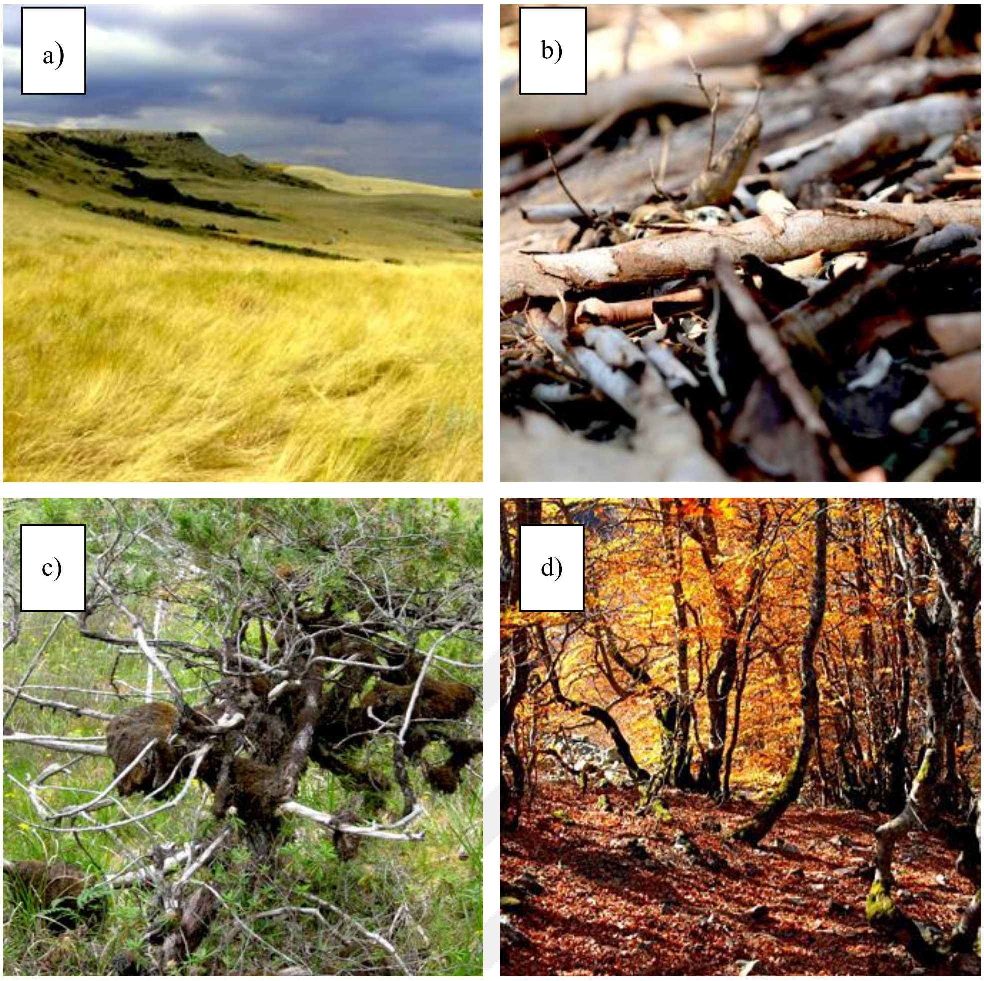

Figure 3.4 Examples of different timelag fuel classess (Url-3).

Body of trees only contribute to the fire if they are completely cured which is unlikely in the most of the situations. Live and dead 1000 hour timelag classes respond to the change in atmospheric state very similarly (Burgan, 1979), therefore their contributions to the fire potential is assessed through relative greenness factor.

Viridity of plants are assessed through remotely sensed data. Normalized Difference Vegetation Index (NDVI) product of European Organization for The Exploitation of Meteorological Satellites (EUMETSAT)'s MSG SEVIRI instrument is chosen as a source. That info is evaluated based on the difference of recent NDVI values from the historical maximums and minimums. Low NDVI readings are assessed as a contribution of live fuels to the dead.

As ten hour timelag fuel yield is determined the next step is to designate their water level. That is accomplished by a formula which evaluates temperature and relative humidity that are downloaded from EUMETSAT. Ten-hour timelag fuel type respond to diurnal changes of relative humidity and temperature very fast. That property is another reason of being chosen as a basis for the fire potential model. If water content of fuels drops below the level of extinction moisture it is regarded as fire initiation is very likely and spread will be fast. Where extinction moisture term defines the level of dryness of the fuel to be able to catch a fire.

FPI model requires live and dead fuel loads and extinction moisture levels of vegetation. The levels of fuel existence and characteristics in different vegetation classes are given in Table 3.1 which is supplied by the study of Laneve and Gadau (2007). Since correspondences of vegetation classes are revealed related field maps of fuel characteristics are created by resampling CORINE 2012 Land Cover data.

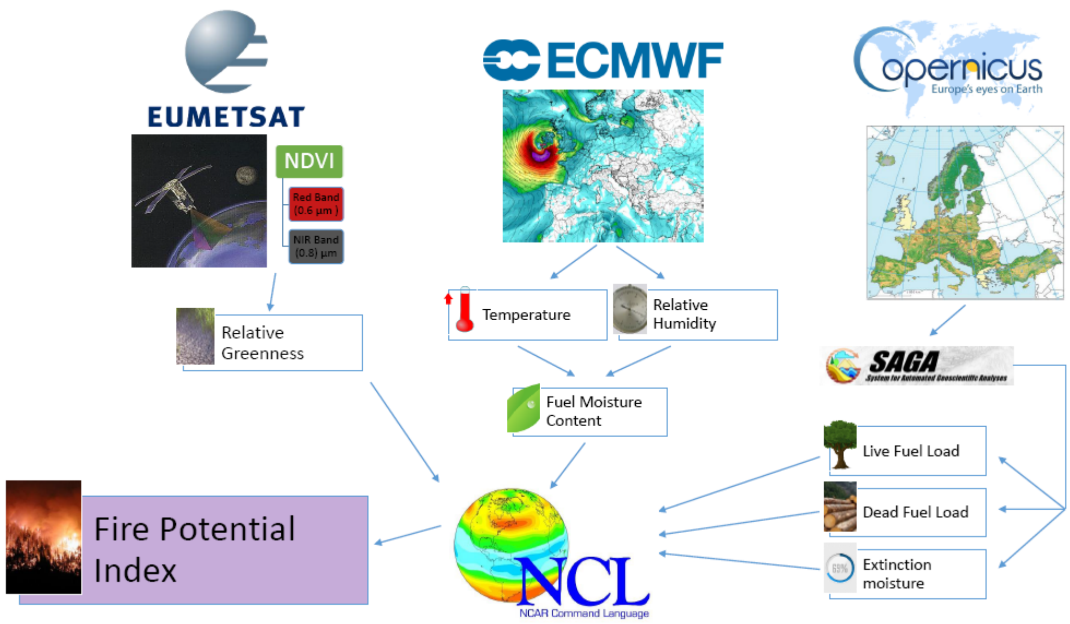

Figure 3.5 Conceptual model of Fire Potential Index.

Conceptual model of FPI is given in Figure 3.5 where sources of data and flow chart of the process is shown. Utilized software in the calculations is also visualized. FPI index evaluated in this study relies on remote sensing, numerical weather prediction model output, and land cover data.

A more detailed description of data sources and computation of the fire models are given in the section below.

3.1 Data

The FPI model requires three main inputs: Fuel type and characteristics, vegetation status, and near surface atmospheric conditions. Data used in this study is descripted in detail in the sections below.

3.1.1 Normalized Difference Vegetation Index (NDVI)

Vegetation status information is accessed through EUMETSAT which is MSG 0 degree daily NDVI product (EUMETSAT, 2015). NDVI indicates degree of photosynthesis activity. NDVI is calculated utilizing 0.6 µm (red band) and 0.8 µm (near infrared band) reflectance bands from SEVIRI Level 1.5 data in which geometric and radiometric corrections are readily applied. Chosen NDVI product of EUMETSAT provides daily maximum, minimum, mean, and aggregated values of NDVI as 10 day composites. Degree of photosynthesis activity is scaled from 0 to 100 as integers, surfaces covered with snow or ice or where cloud cover blocks surface are represented with 255 value. 2012.01.01 to 2016.12.31 period downloaded from EUMETSAT Data Centre as Hierarchical Data Format 5 (HDF5) in order to obtain historical maximum and minimum values as 10 day composites. Data resolution is approximately 3km at the Greenwich Meridian and Equator intersection point and steadily decrease as we move away. NDVI data is interpolated to a regular 0.04x0.04 degree resolution (very close to a native resolution of MSG data over Turkey) grid system on which calculations are evaluated. Interpolation performed using nearest neighbor methods. Distribution of satellite observation points on regular latitude longitude projection is demonstrated in Figure 3.6. Historical maximum and minimum fields of considered period are represented in Figure 3.7 and Figure 3.8.

MSG satellite is geostationary which means it has a fixed position compared to Earth at 36000km altitude. Remoteness cause a decrease in spatial resolution of satellite imagery but allows to complete a full disc scan of Earth in every 15 minutes. Although higher resolution satellite imagery products are available such as Moderate Resolution Imaging Spectroradiometer (MODIS) at 250 meter spatial resolutions, they can only provide data on daily basis since they are polar orbiters. If the operational use of FPI is intended, high frequency temporal data might provide more realistic vegetation status.

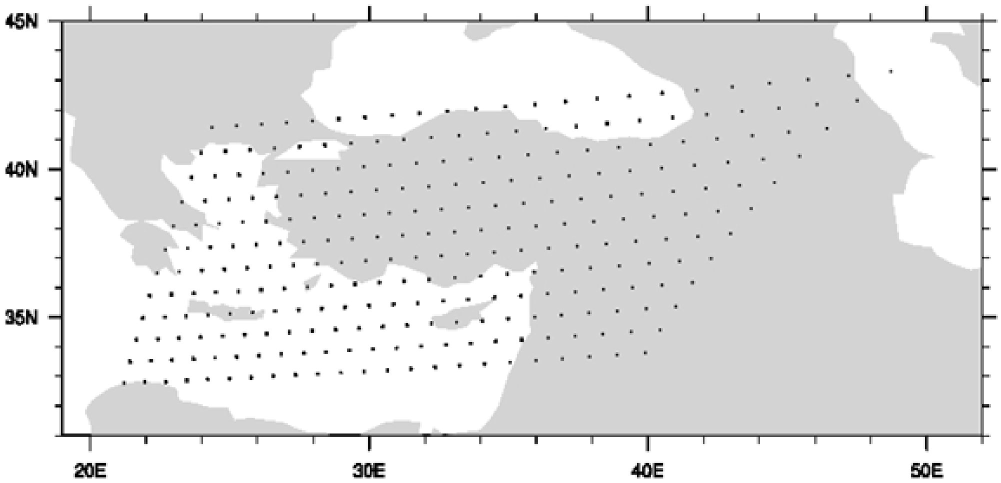

Figure 3.6 Spatial distribution of MSG grid centers on regular lat lon projection.

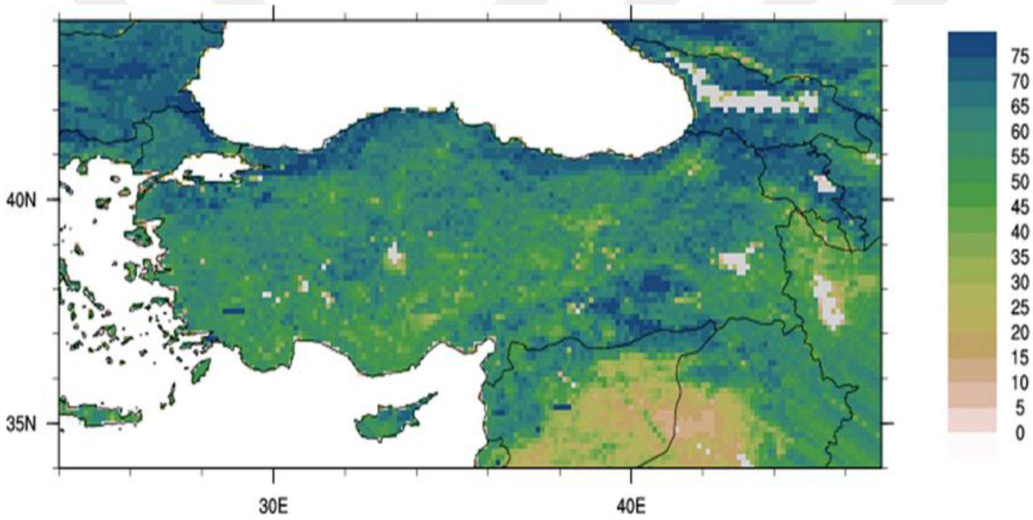

Figure 3.7 Maximum NDVI values for 2012-2016.

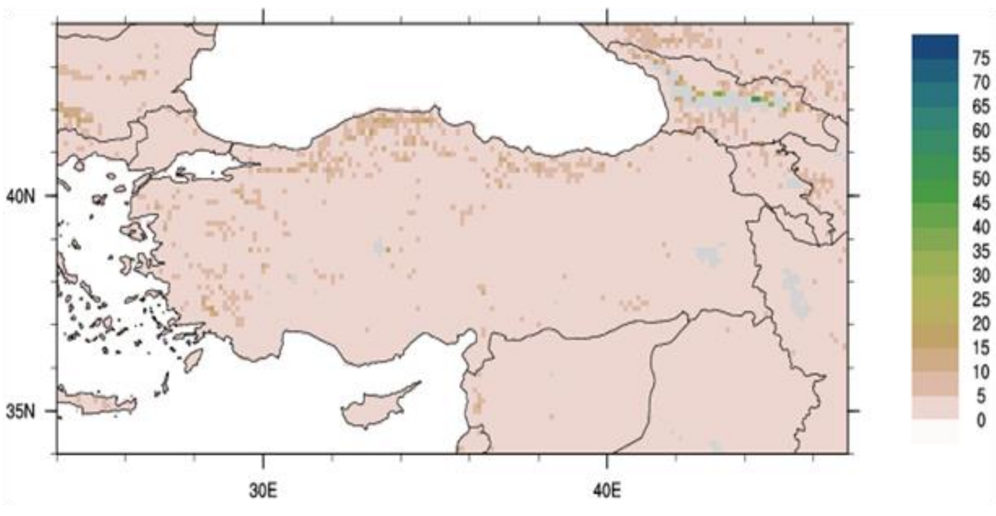

Figure 3.8 Minimum NDVI values for 2012-2016.

3.1.2 Meteorological Parameters

Meteorological fields are downloaded from European Centre of Medium Range Forecasts (ECMWF, 2016). ECMWF provides both analysis and forecast fields. Analysis data is chosen, which is produced utilizing model runs and data assimilations of satellite, radiosonde and gauge observations. Analysis data has four cycles per day which are 00:00, 06:00, 12:00, and 18:00 UTC. 12:00 UTC are evaluated in this study since it's the time of day at which fire risk is virtually at its peak. Horizontal resolution of data is approximately 9 km degree which is constructed as regular latitude-longitude grids. Required inputs of meteorological data for FPI are 2-meters surface temperature and relative humidity. Since ECMWF model does not provide relative humidity it is derived using 2-meters dew point temperature, and 2-meters temperature (Dutton, 1976). A significant benefit of using numerical weather model output fields is to acquire spatially continuous data. Gauge readings are considered as ground truth but they are only available in particular locations. FPI needs spatially continuous data. In order to meet this requirement interpolation method, need to be applied. Success of almost every interpolation method rely on the densely located gauge network. Unluckily forests are placed on mountainous areas where observations are sparse. Using numerical weather prediction model data is a sound alternative compared to gauge data since unlike interpolation methods numerical weather prediction models evaluate deterministic equations to assess atmospheric conditions.

3.1.3 CORINE 2012 Land Cover

Fuel related fields are generated based on CORINE Land Cover (CLC) 2012 data. Saga GIS software is used to re-project and reclassify 250 meter horizontal resolution CLC data into 0.04 degree regular latitude-longitude grids. Most frequent value method is chosen as a re-sampling option. Choosing coarse resolution is a result of using satellite imagery fields as a basis and it might have caused data loss in terms of detail and also lead misrepresentations in particular locations. Coarse resolution is also compromised for computation efficiency. On the other hand, downscaling meteorological fields into finer resolution just by interpolation methods might also produce errors due to complex topography of Turkey. 250 meter resolution clipped CLC data for study area could be seen in Figure 3.9. Re-gridded CLC data is visualized in Figure 3.10. Fuel types described in Burgan's study has a broader range of classes.

Fuel types defined in this study are adapted from the table provided by Laneve and Gadau (2007)'s work could be seen in Table 3.1. CORINE has limited classes of vegetation specifically in forest classification. Classes outside of Table 1 are masked and remaining available data is visualized in Figure 3.11.

Table 3.1 Correspondence between CORINE vegetation types and fuel models (Laneve and Gadau, 2007)

NFDR Model	Fuel Load Live (T/a)	Fuel Load Dead (T/a)	Ext. Moisture (%)	Vegetation Type (CORINE)
GR2	1	0.1	15	2.1.1
GR4	0.25	1.9	15	2.3.1
GS2	1.6	0.5	15	2.4.3
Albini 3	0	3	25	2.4.4
TU1	0.2	1.1	20	3.1.1
TU4	4.5	2	12	3.1.2
TU5	3	4	25	3.1.3
Albini 1	0	0.74	12	3.2.1
SH2	3.8	1.4	15	3.2.2
SH7	3.4	3.5	15	3.2.3
Albini 6	0	6.0	25	3.2.4

Figure 3.9 CORINE Land Cover 2012, clipped and reprojected.

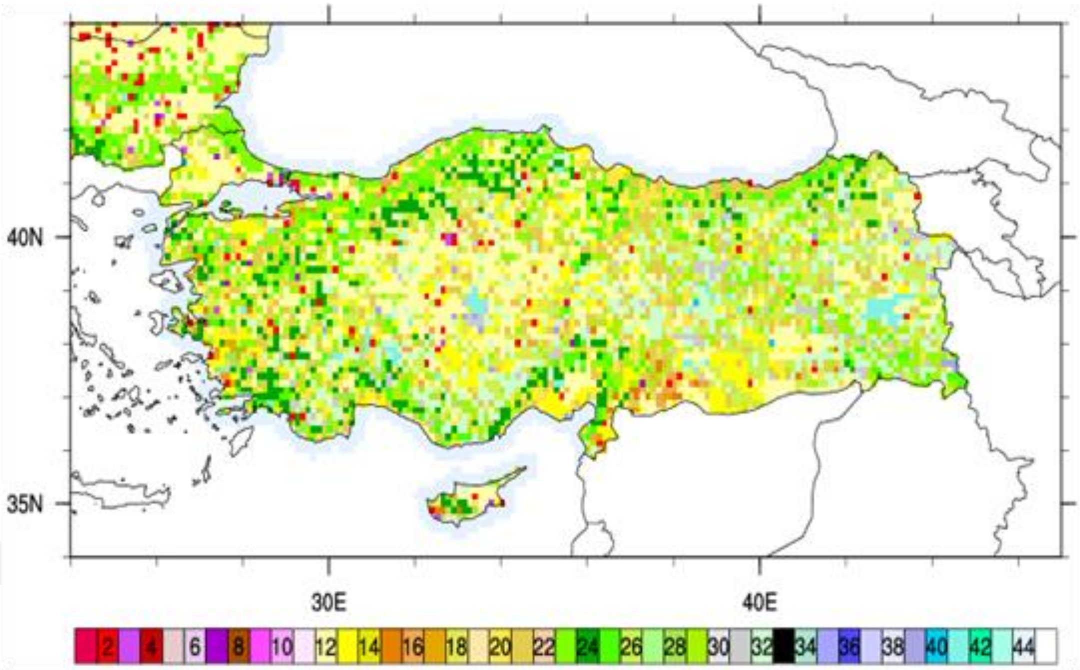

Figure 3.10 Resampled CORINE Land Cover 2012.

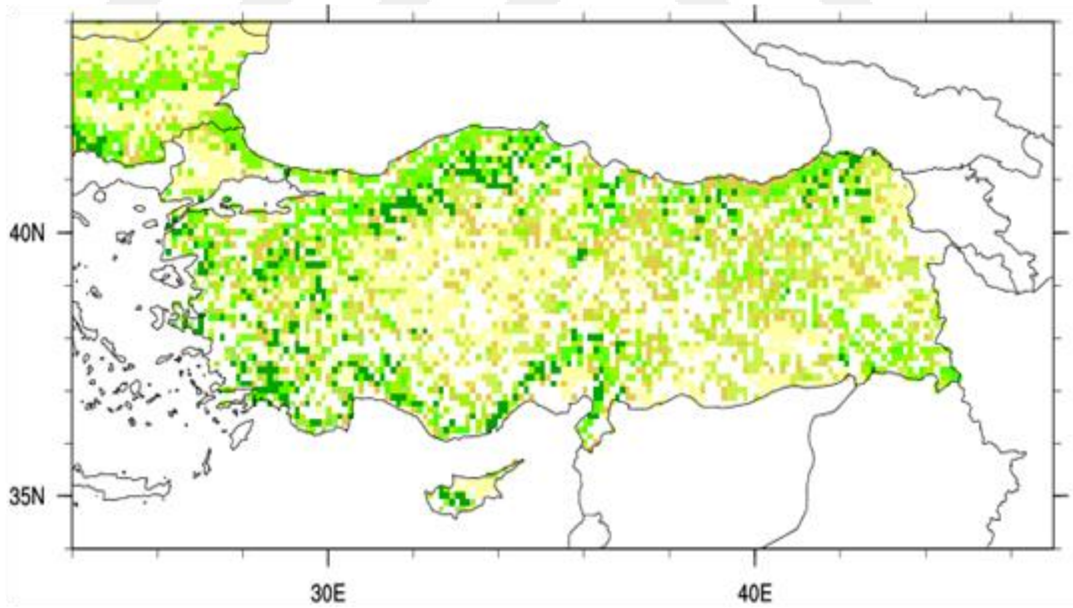

Figure 3.11 Resampled and Masked CORINE Land Cover 2012.

Table 3.2 CLC Classes visualized in Figure 2 where fields evaluated in FPI are highlighted in yellow.

Grid Code	CLC Code	Label 1	Label 3
1	111	Artificial surfaces	Continuous urban fabric
2	112	Artificial surfaces	Discontinuous urban fabric
3	121	Artificial surfaces	Industrial or commercial units
4	122	Artificial surfaces	Road and rail networks and associated land
5	123	Artificial surfaces	Port areas
6	124	Artificial surfaces	Airports
7	131	Artificial surfaces	Mineral extraction sites
8	132	Artificial surfaces	Dump sites
9	133	Artificial surfaces	Construction sites
10	141	Artificial surfaces	Green urban areas
11	142	Artificial surfaces	Sport and leisure facilities
12	211	Agricultural areas	Non-irrigated arable land
13	212	Agricultural areas	Permanently irrigated land
14	213	Agricultural areas	Rice fields
15	221	Agricultural areas	Vineyards
16	222	Agricultural areas	Fruit trees and berry plantations
17	223	Agricultural areas	Olive groves
18	231	Agricultural areas	Pastures
19	241	Agricultural areas	Annual crops associated with permanent crops
20	242	Agricultural areas	Complex cultivation patterns
21	243	Agricultural areas	Land principally occupied by agriculture,
22	244	Agricultural areas	Agro-forestry areas
23	311	Forest and semi natural areas	Broad-leaved forest
24	312	Forest and semi natural areas	Coniferous forest
25	313	Forest and semi natural areas	Mixed forest
26	321	Forest and semi natural areas	Natural grasslands
27	322	Forest and semi natural areas	Moors and heathland
28	323	Forest and semi natural areas	Sclerophyllous vegetation
29	324	Forest and semi natural areas	Transitional woodland-shrub
30	331	Forest and semi natural areas	Beaches, dunes, sands
31	332	Forest and semi natural areas	Bare rocks
32	333	Forest and semi natural areas	Sparsely vegetated areas
33	334	Forest and semi natural areas	Burnt areas
34	335	Forest and semi natural areas	Glaciers and perpetual snow
35	411	Wetlands	Inland marshes
36	412	Wetlands	Peat bogs
37	421	Wetlands	Salt marshes
38	422	Wetlands	Salines
39	423	Wetlands	Intertidal flats
40	511	Water bodies	Water courses
41	512	Water bodies	Water bodies
42	521	Water bodies	Coastal lagoons
43	522	Water bodies	Estuaries
44	523	Water bodies	Sea and ocean
48	999	NODATA	NODATA
49	990	UNCLASSIFIED	UNCLASSIFIED LAND SURFACE
50	995	UNCLASSIFIED	UNCLASSIFIED WATER BODIES
255	990	UNCLASSIFIED	UNCLASSIFIED

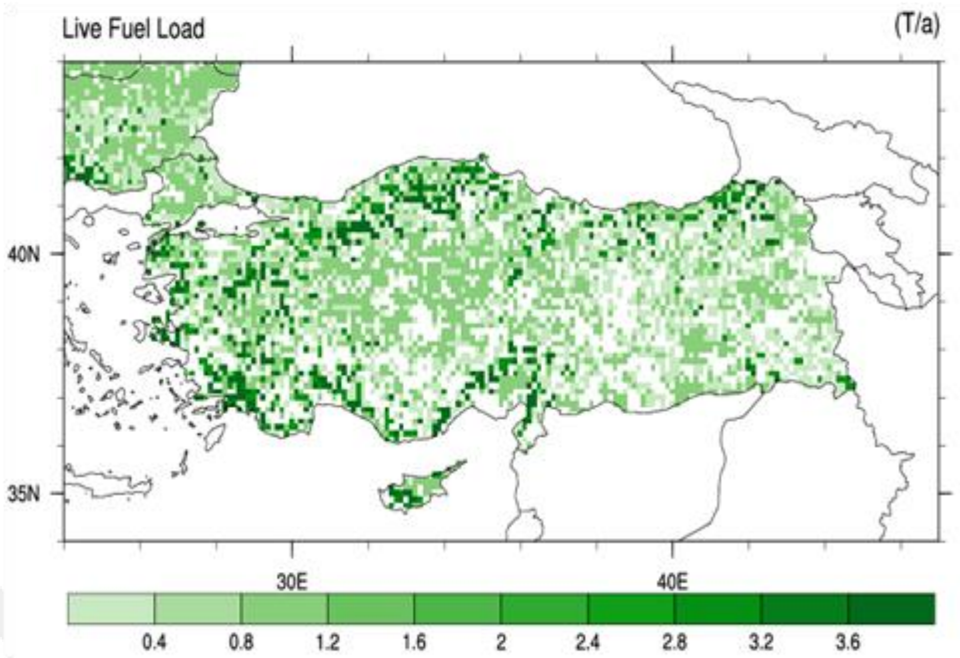

Figure 3.12 Live fuel load derived from CLC.

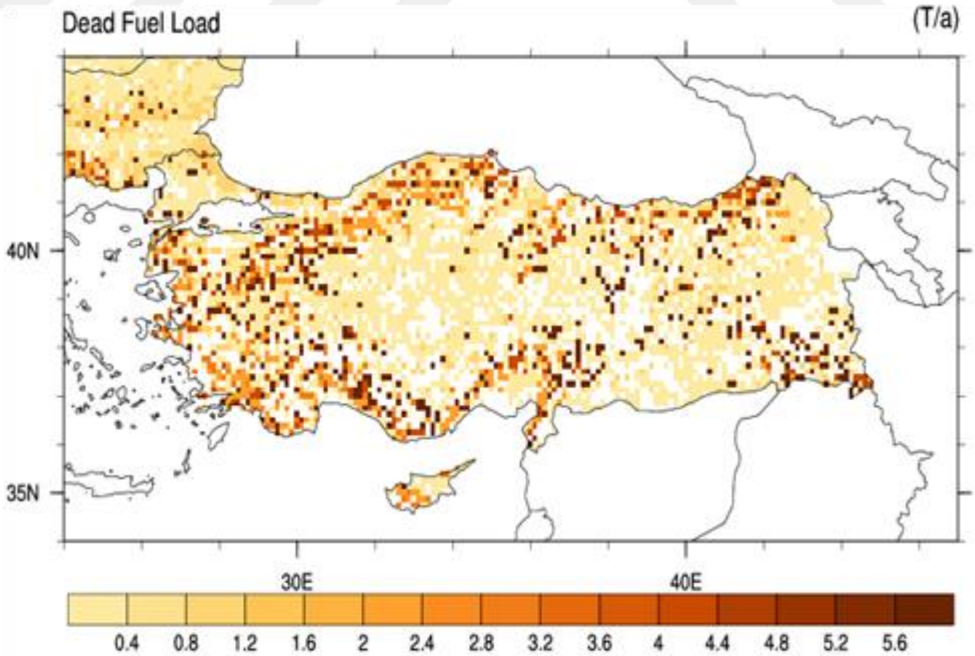

Figure 3.13 Dead fuel load derived from CLC.

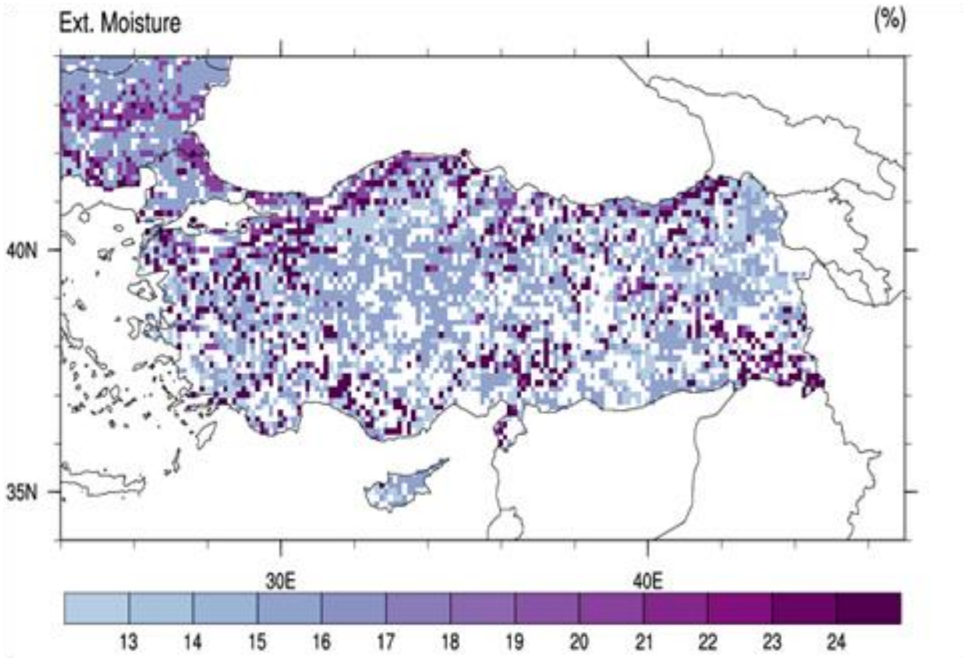

Figure 3.14 Extinction moisture derived from CLC.

Fuel data characteristics are examined in three different fields: Live fuel load, dead fuel load, and extinction moisture. Fields are reclassified based on resampled data that is shown using equivalences in Table 3.1.

3.2 Instruments

Most of the calculation and visualization efforts are performed by open source or free software which runs on Linux environment. NCL (The NCAR Command Language, 2017) software was used in order to evaluate calculations of FPI model which incorporates raster data. NDVI composites of EUMETSAT in HDF5 format were also resampled and evaluated by NCL is developed by National Center of Atmospheric Research Center in America. It supports input/output of many data formats and has numerous built in functions of statistics, and mapping. Projection, regridding, and resampling of CORINE CLC data was performed by another open source software Saga GIS. Both software has a vast community, good online documentation and user support platforms even though they are free to use. Statistical calculations were performed by Statistical Package for Social Sciences (SPSS), version 21.

3.3 Calculation of Fire Potential Index

Calculate the ten-hour timelag fuel moisture using equilibrium moisture content

$$FM_{10} = 1.28 * emc$$

where

$$emc = 2.22749 + 0.16011 * rh - 0.014784 * T,\ if\ 10\% \leq rh \leq 50\%$$

$$emc = 21.061 + 0.00557 * rh^2 - 0.00035 * rh * T - 0.4832 * rh,$$
$$if\ rh > 50\%$$

$$emc = 0.0323 + 0.28107 * rh - 0.000578 * rh * T,\ if\ rh < 10\%$$

where rh and T are relative humidity and air temperature which are corrected for solar heating (Fosberg and Deeming, 1971)

Formulas which are provided below were taken from the study of Burgan and colleagues (1998; pp. 164-166).

$$RG = (ND_o - ND_{mn})/(ND_{mx} - ND_{mn}) * 100$$

where

RG = relative greenness

ND_O = highest observed NDVI value for the 10 day composite period

ND_{mn} = historical minimum NDVI value for a given pixel

ND_{mx} = historical maximum NDVI value for a given pixel

Set the fire potential index to zero

$$FPI = 0 \tag{1}$$

Convert RG to a fractional value

$$RG_f = \frac{RG}{100} \tag{2}$$

Relative greenness is converted to a ratio in order to determine the live fuel load assigned to the pixel.

$$LL_p = RG_f * LL_{fm} \tag{3}$$

where

LL_p = live fuel load for the pixel

LL_{fm}= live fuel load for the model

Cured live fuel load and dead live fuel load are summed and assigned to the pixel.

$$DL_p = (1 - RG_f) * LL_{fm} + DL_{fm} \tag{4}$$

where

DL_p = dead fuel load for pixel

DL_{fm}= dead fuel load for the fuel model

Remaining executions are to be performed only if DL_p is greater than zero. Calculate the fraction of the live fuel load.

$$L_f = LL_p \,/\, (LL_{fm} + DL_{fm}) \tag{5}$$

Calculate the fraction of the total fuel model that is dead

$$D_f = DL_p \,/\, (LL_{fm} + DL_{fm}) \tag{6}$$

Fractional 10-h TLFM is normalized on dead fuel moisture of extinction (MX_d) for the model, which are defined in Table 3.1 Ten hour fuel moisture (FM_{10}) is normalized to the moisture of extinction to scale it as the same fraction of relative greenness.

$$TN_f = FM_{10} \,/\, MX_d \tag{7}$$

where

TN_f = fractional ten-hour timelag fuel moisture

FM_{10} = ten hour moisture (percent)

MX_d = dead fuel extinction moisture (percent)

Relative greenness is a replacement for live moisture in the FPI. When live moisture is at its highest relative greenness approaches 1, as live moisture decrease some of the live vegetation will be dried out.

$$FPI_u = 100 - \left(RG_f L_f + TN_f D_f\right) * 100 \quad (8)$$

where

FPI_u = uncorrected fire potential index

At the equation (8) maximum value of FPI is limited by TN_f term due to dead fuel moisture of extinction.

$$FPI_{max} = 100 - \frac{2}{MX_d} * 100 \quad (9)$$

where

FPI_{max} = maximum uncorrected fire potential index value

Following equation is need to be applied in order to limit FPI values between 1 to 100

$$FPI = FPI_u + \frac{2}{FPI_{max}} * \frac{FPI_u}{FPI_{max}} * 100 \quad (10)$$

where

FPI = final fire potential index value

4. RESULTS

As FPI outputs are examined, it was found out that FPI reasonably addresses regions where wildfires are frequent. Index also simulates sudden changes of fire likelihood by the utilization of diurnal meteorological data produced by numerical weather prediction model, and recent vegetation status acquired by remote sensing methods. However, as forest fire occurrences are compared with the FPI outputs, some particular index values are considered to be low in order to successfully indicate a possible fire event. Burgan and his colleagues' study (1998) suggests that fire occurrences are unlikely when FPI score is below 15. FPI scores of each fire incident are paired with the cause information of fire data is shown in Figure 4.1. Although most of the fire events occur above the score of 20 which is the threshold for the low label of FPI mappings, score of 556 fire events out of 3181 were below 15 and 695 of them were below 20.

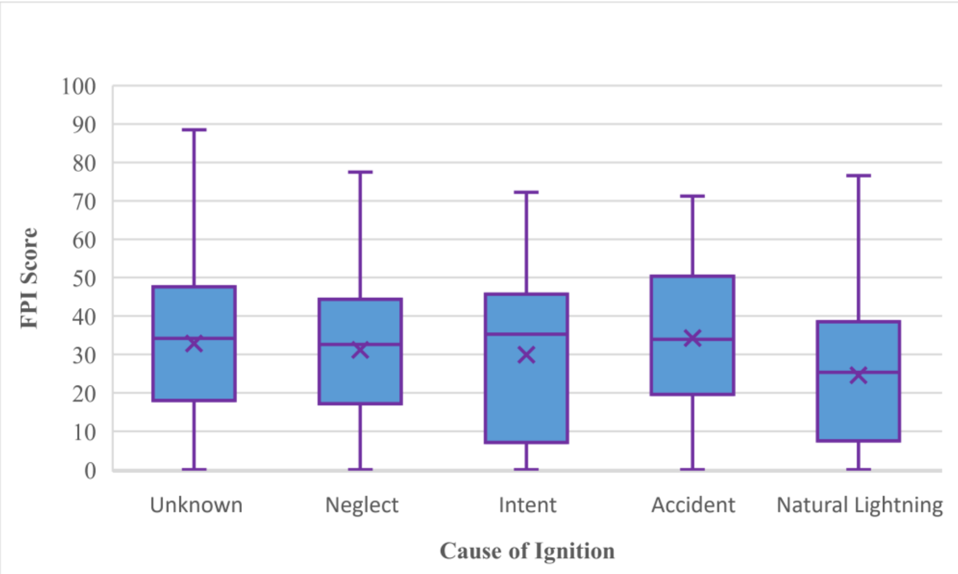

Figure 4.1 Distribution of FPI scores based on ignition causes.

As provided in Figure 4.1 lowest FPI scores are grouped under "Natural Lightning" class. This is an expected result since lightning are followed by storms which will lead to a sudden decrease in fire potential. Intentional fires have the broader range of FPI score due to purpose driven nature of fire initiation. Some of the fire events unsuccessfully indicated by FPI is thought to be a result of inaccurate coordinate addressing. Turkey has a complex topography and forest are mostly placed on those mountainous areas therefore spatial weather and vegetation conditions change rapidly. Misplaced fire coordinates might lead to inaccurate assessment of FPI scores. This foresight is supported by the evidence of monthly correlational statistics between FPI values and fire occurrences. Seasonal deviation of these two variables were highly coherent.

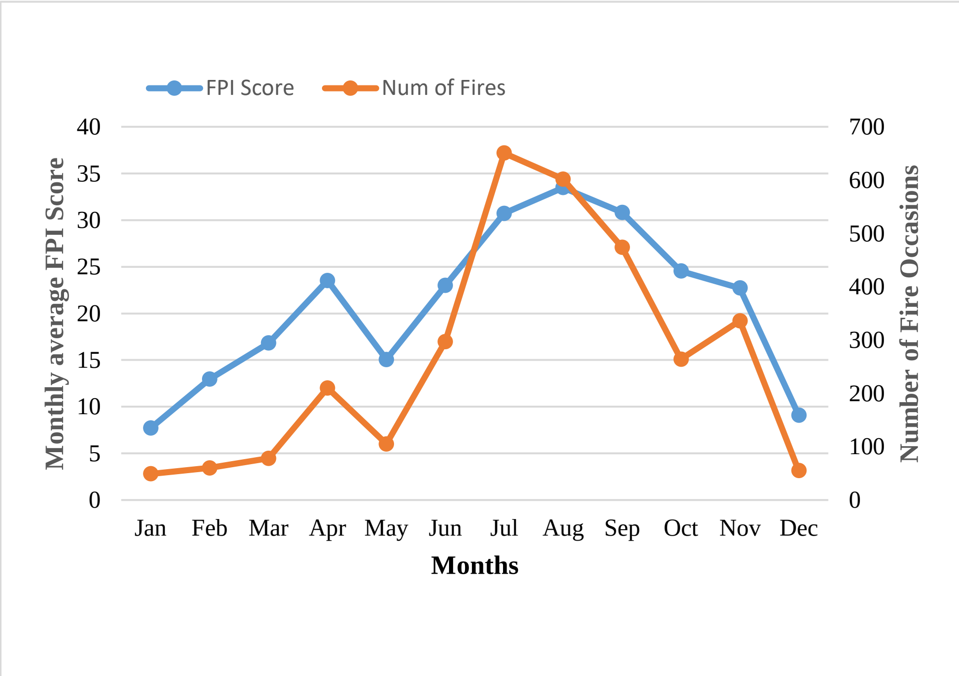

Figure 4.2 Monthly values of areal average of FPI scores over Turkey in 2016 and number of fire occurrences of the according months.

In order to statistically investigate correlation between monthly deviation of areal averages of FPI scores over Turkey and number of fire event which is also seen in Figure 4.2. Pearson's correlation analysis was further performed by using the Statistical Package for Social Sciences (SPSS), version 21. Findings revealed that monthly FPI scores and monthly number of fires were strongly correlated, $r = .93$, $p < .01$.

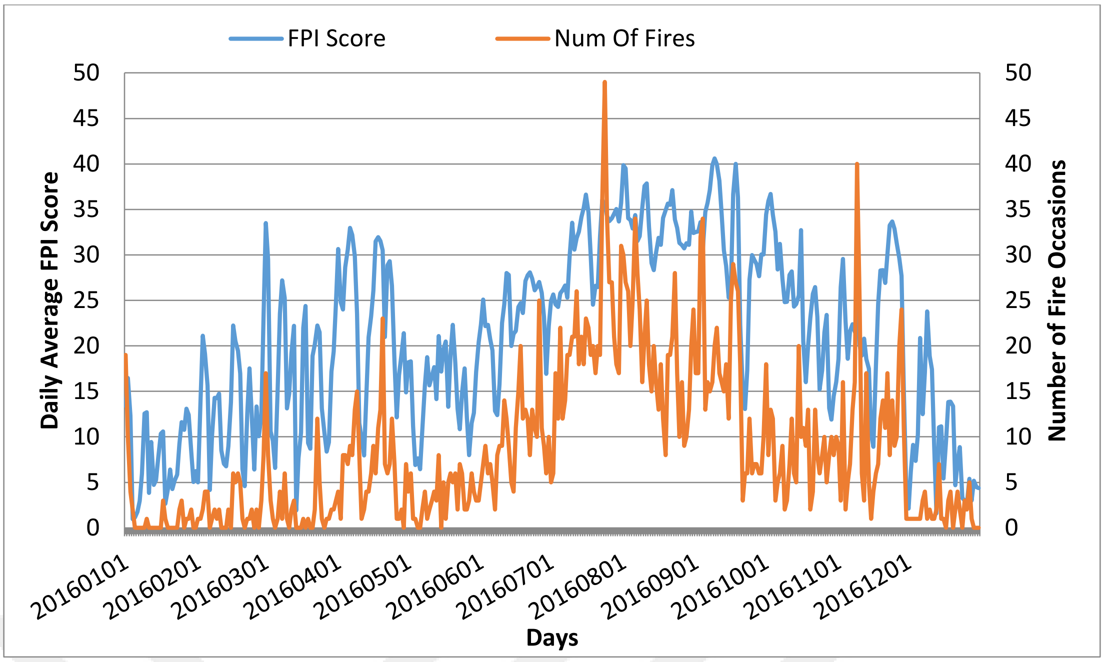

Figure 4.3 Daily values of areal average of FPI scores over Turkey in 2016 and number of fire occurrences of the according days.

Pearson's correlation analysis was also performed for testing correlations between daily FPI scores and daily fire occurrences. Findings showed that daily FPI scores and daily number of fires were strongly correlated, $r = .74$, $p < .01$. Figure 4.3 visualizes relationship between daily fire occurrences and FPI scores.

Relationship between burnt area in fire incidents and FPI score were also examined and it was discovered that there is no association between these parameters. Burned area and FPI are appeared to be independent from each other.

Calculated FPI scores were mapped for the whole coverage of Turkey. FPI scales were from 0 to 100 where 0 indicates virtually no risk and 100 indicates extreme levels of fire probability. In order to ease interpreting, 0 to 100 numerical scale converted into low, moderate, high, very high, and extreme risk labels with 20 point intervals. Water bodies were indicated with turquoise. Cultivated or build up lands where there are no forest or artificial effects like irrigation practices take place were shown with gray color and land label. Areas where remote sensing data was unavailable due to cloud cover, snow or ice were indicated with light blue and no data label.

Risk maps of FPI are provided in detailed in between Figure 4.4 and Figure 4.14.

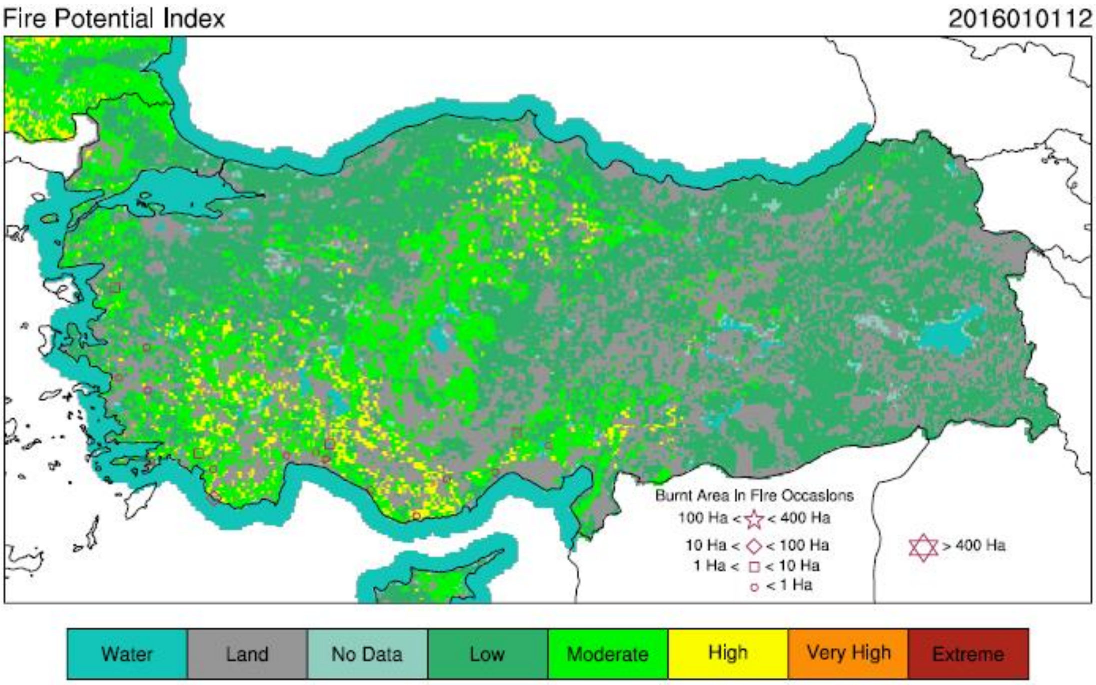

Figure 4.4 FPI scores and fire events in 2016-01-01.

Winter is a season when forest fires were less expected, however, as presented in Figure 4.4, 19 individual fires occurred in the first day of 2016. Moderate risk was indicated for the most parts of Mediterranean region where high risk ranking was also abundant.

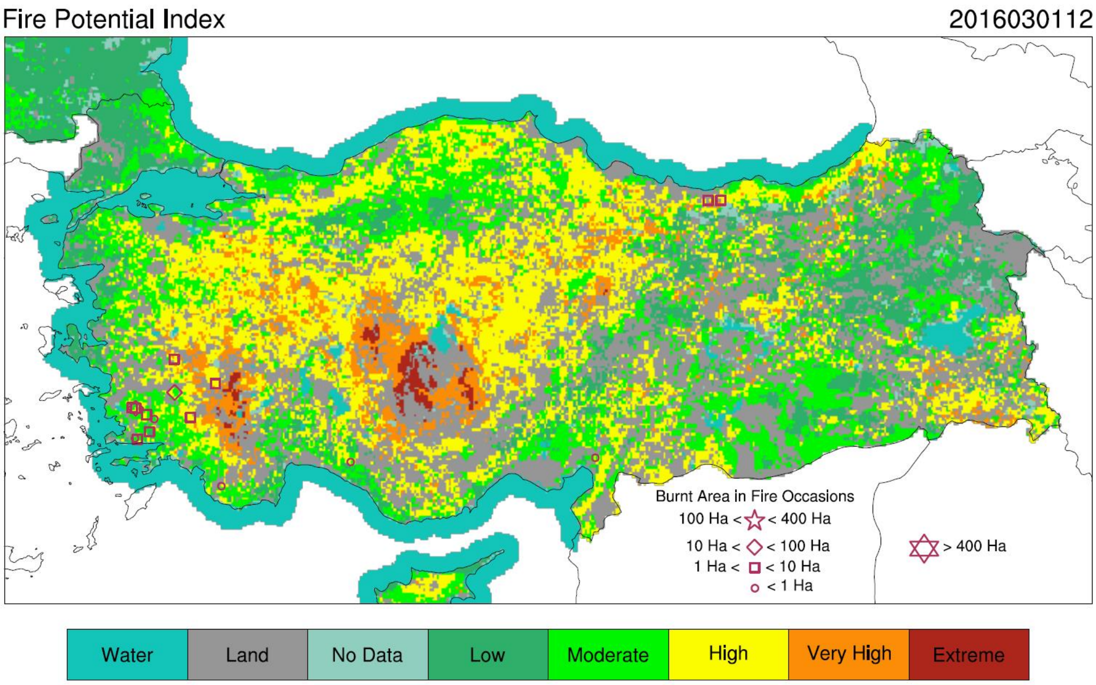

Figure 4.5 FPI scores and fire events in 2016-03-01.

Figure 4.5 presents that 17 fires occurred which resulted in burning of 93.8 hectares of forest land in 1st of March. This particular day was the second most fire emerged day of spring. High levels of risk was indicated for this day. In the inlands, even extreme risk was estimated. Fires occurrences were paired with moderate or high risk rankings.

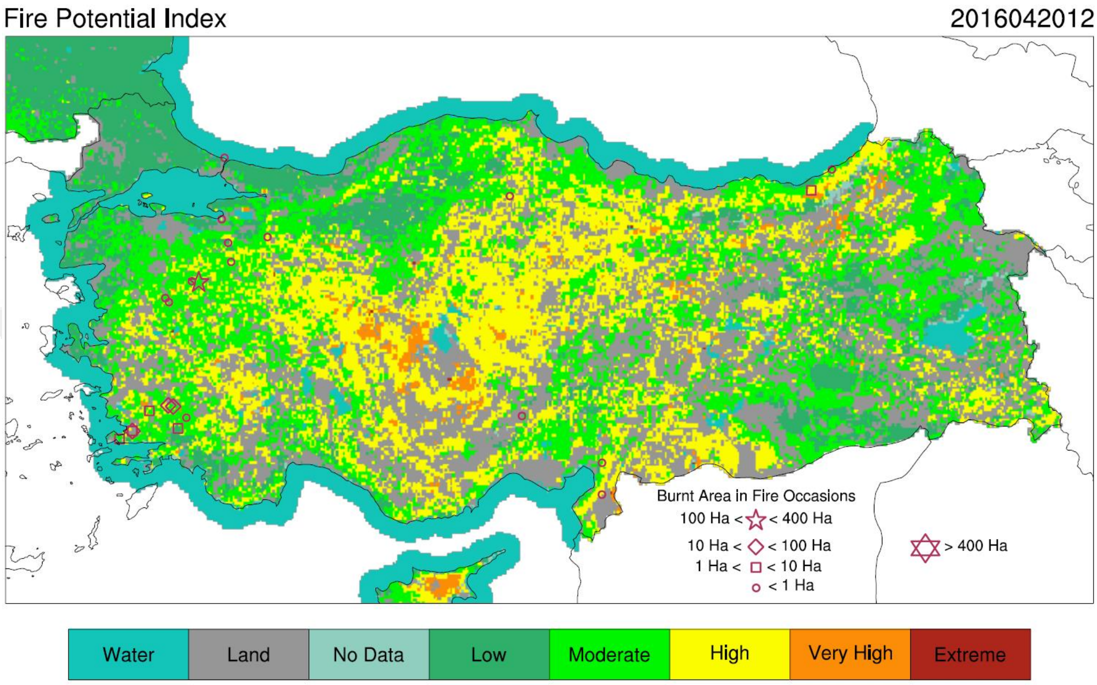

Figure 4.6 FPI scores and fire events in 2016-04-20.

Figure 4.6 shows that 20th of March was the third most fire emerged day of spring with total 319,4 hectares of forest was burned. Most of the fires occurred around Muğla, Balıkesir, and Rize. Moderate or high FPI score was signaled.

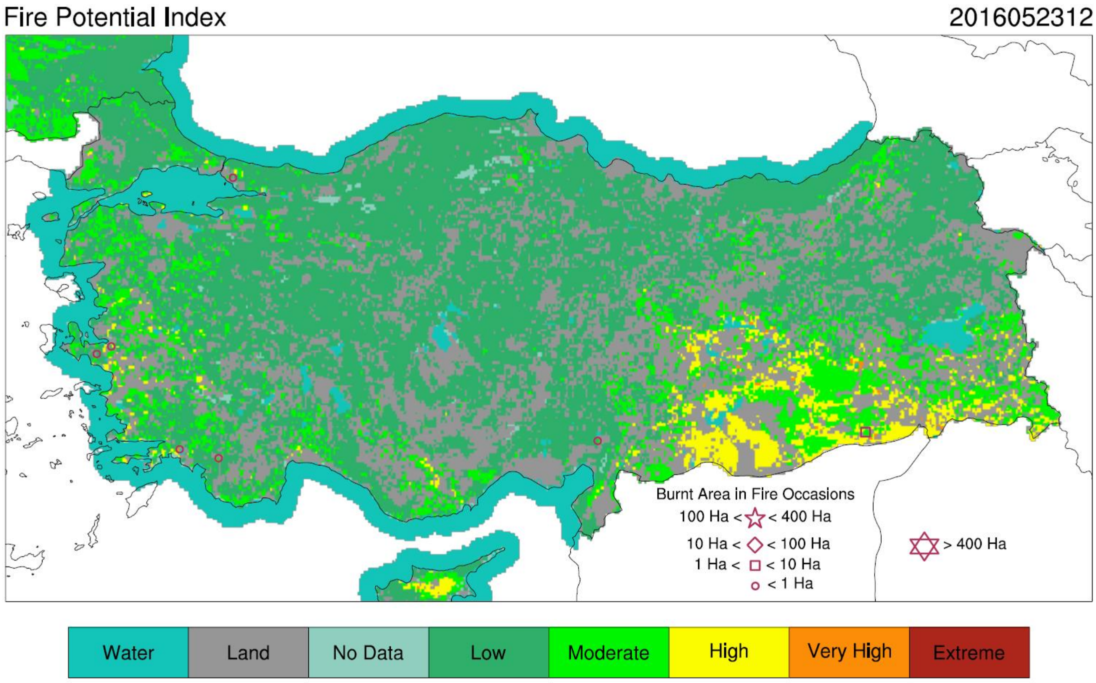

Figure 4.7 FPI scores and fire events in 2016-05-23.

As presented in Figure 4.7, days with low level of fire activity was also indicated successfully. In general, end of May is a time when forest fires are more frequent. However, fire potential was lower in 2016-05-23 than expected.

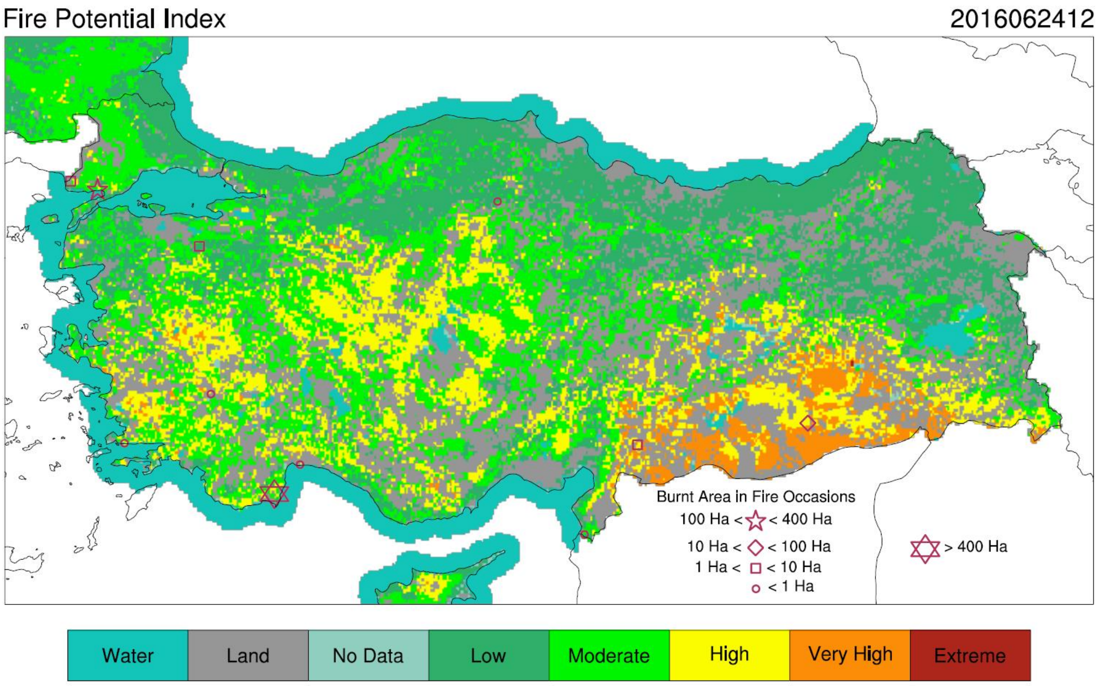

Figure 4.8 FPI scores and fire events in 2016-06-24.

Two big fires were experienced in 2016-06-24 as seen in Figure 4.8. Moderate risk was signaled for the fire in Antalya in which 1317.3 hectares of forest area were burned. In Edirne, 350 hectares of forest area were damaged where was assumed to have moderate fire risk.

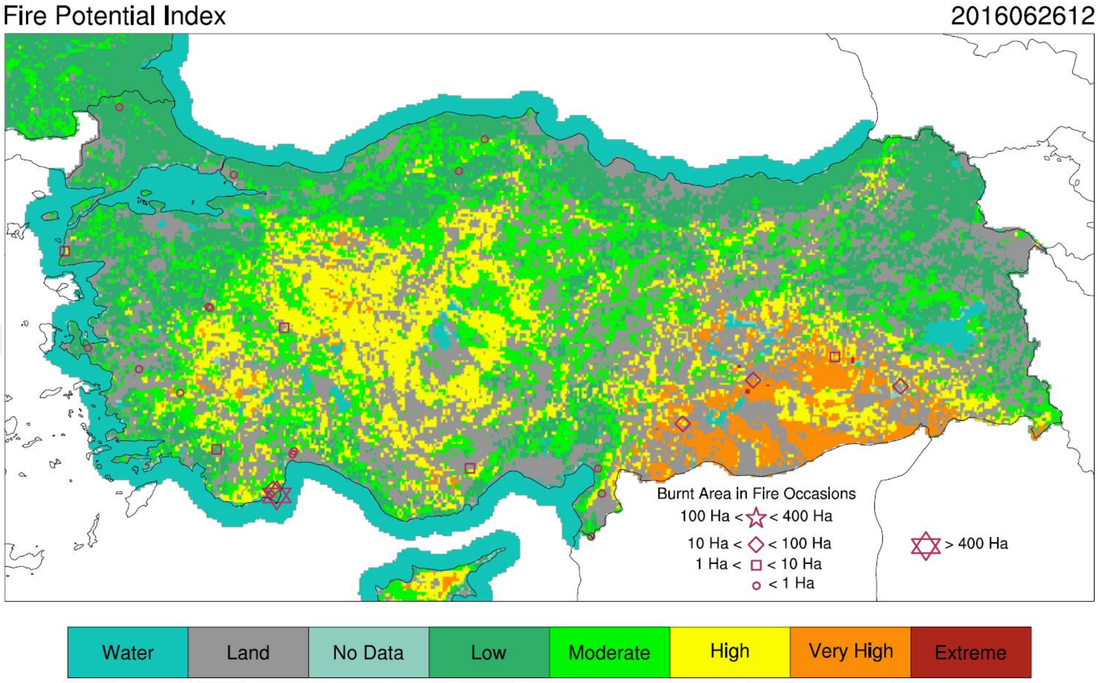

Figure 4.9 FPI scores and fire events in 2016-06-26.

Figure 4.9 represents that 25 fire occurrences were recorded in 2016-06-26. 532 hectares of forest were destroyed in Antalya. In Southeastern Anatolia Region, moderate range of hectares of forest land were burned for very high risk was estimated.

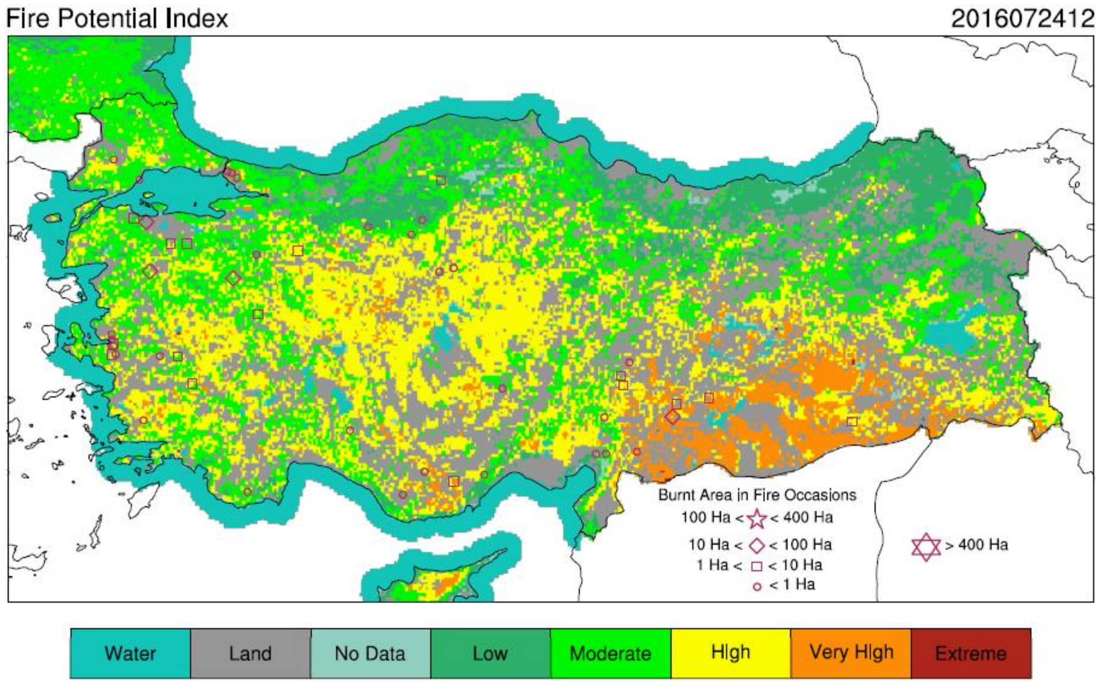

Figure 4.10 FPI scores and fire events in 2016-07-24.

Figure 4.10 demonstrates a particular day which is the most fire emerged day of 2016. 49 fires were occurred causing destruction of 167.3 hectares of forest cover. High levels of fire potential was signaled for the most of the Turkey except Black Sea region where there was only one fire occasion.

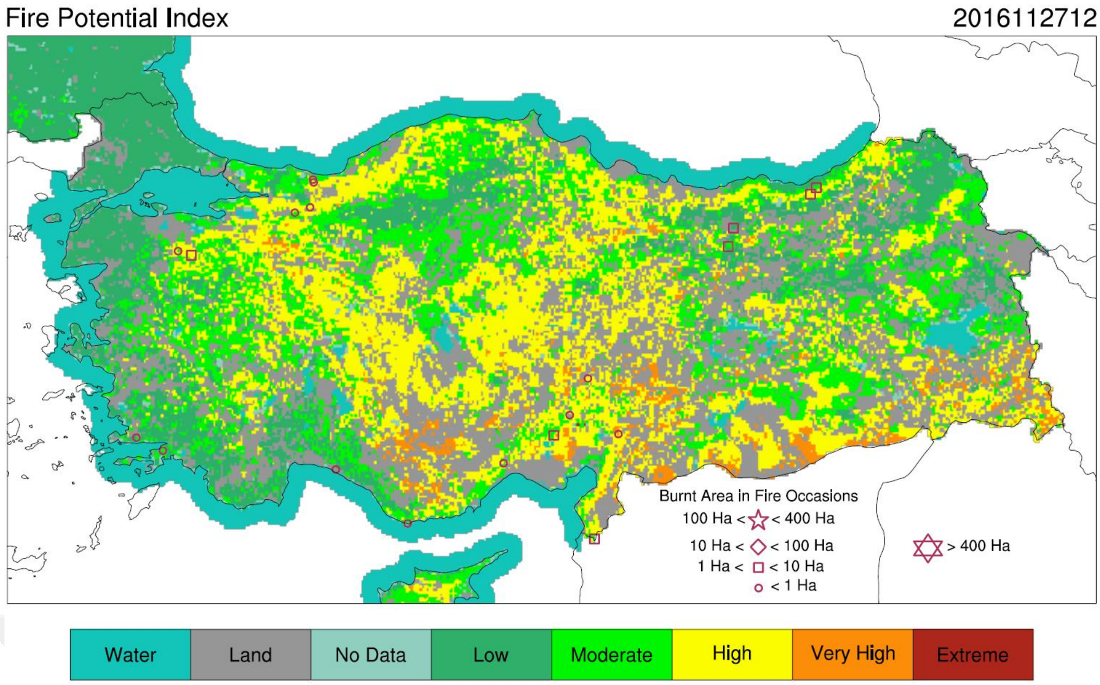

Figure 4.11 FPI scores and fire events in 2016-11-27.

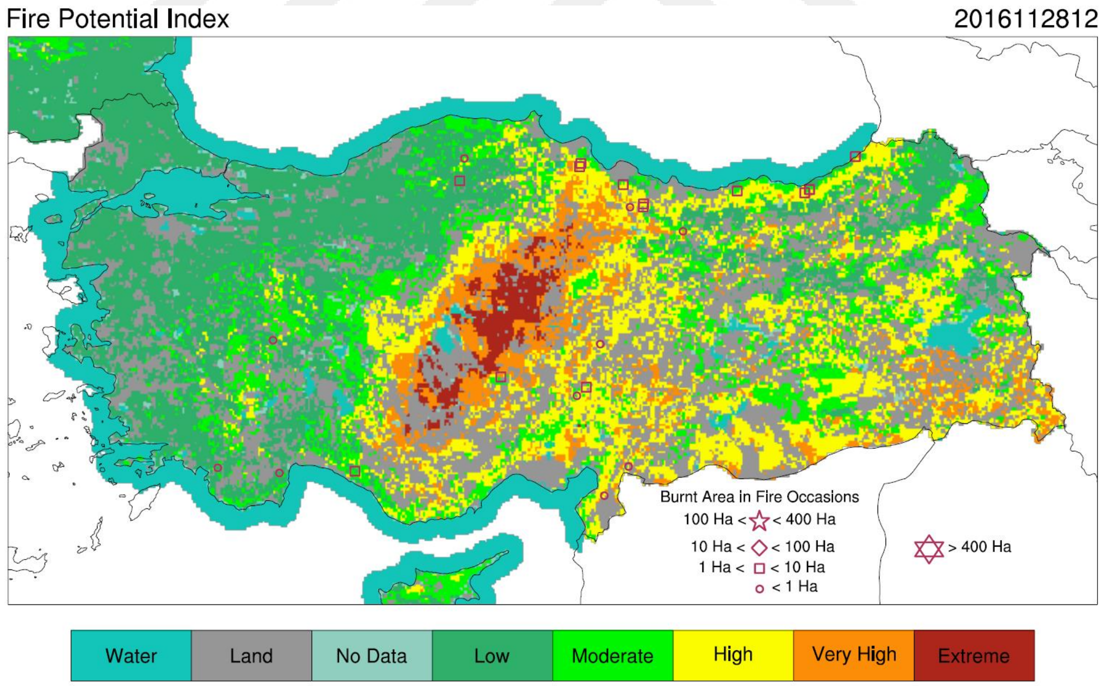

Figure 4.12 FPI scores and fire events in 2016-11-28.

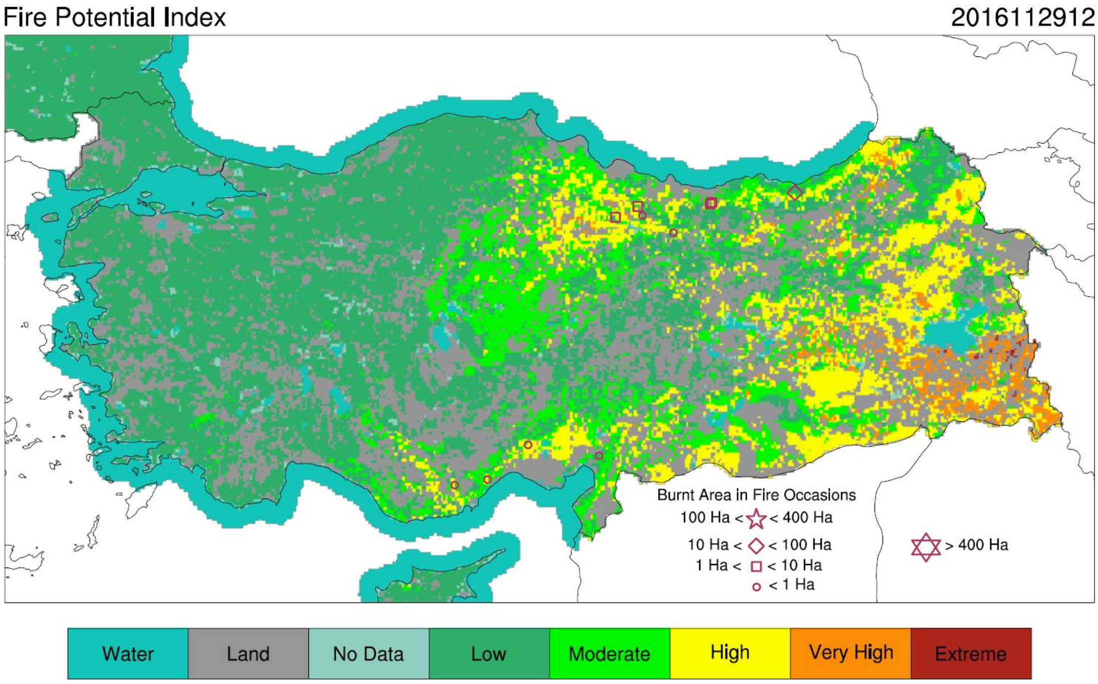

Figure 4.13 FPI scores and fire events in 2016-11-29.

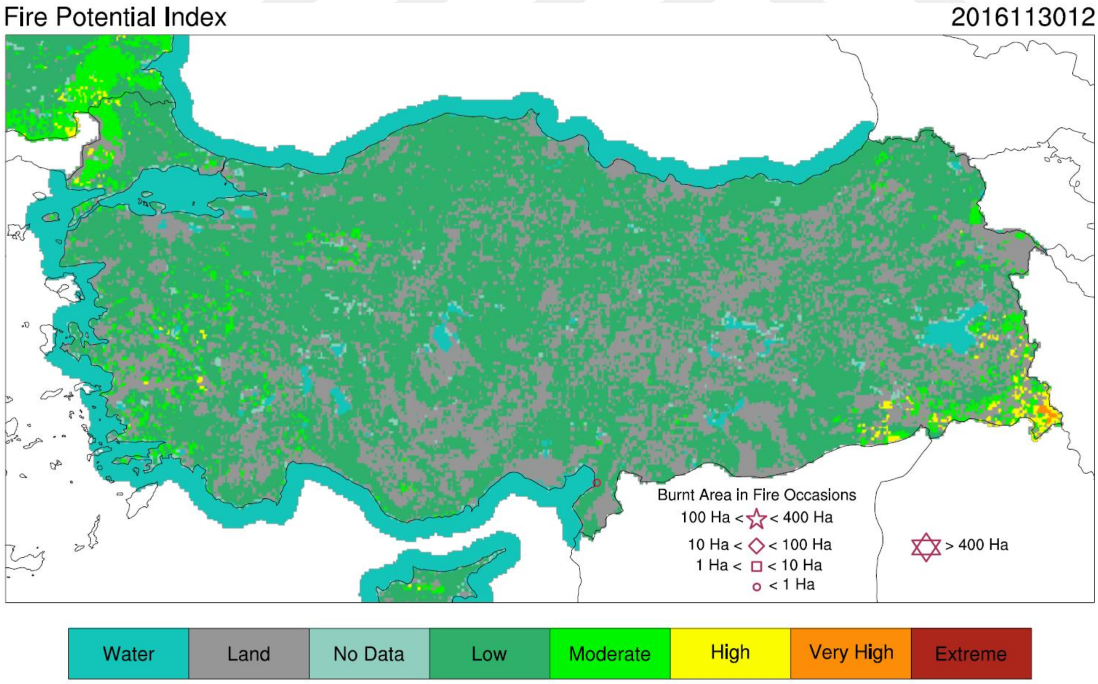

Figure 4.14 FPI scores and fire events in 2016-11-30.

Four consecutive days were mapped in between Figure 4.11 and Figure 4.14. Dramatic change of fire potential accordance with fire occasions were successfully demonstrated. This was resulted from a cold front passage moving from west to east. Sudden change of fire potential and migration of fire occurrences were in good agreement.

5. DISCUSSION

In this study, success of FPI method was investigated for Turkey for the year of 2016 utilizing numerical weather prediction fields and remote sensing imagery. Findings of this study revealed that FPI is a good indicator of fire potential and it can mimic change of fire occurrences not only in seasonal but also daily scale. Statistical analyses were further proved the correlation between fire occurrences and FPI scores.

The present study showed that there was no relationship between burnt area and fire potential score. This situation was a result of absence of meteorological driver fields of wind speed, and stability which determine burnt area. In addition, terrain slope and aspect have influences on fire spread.

Based on the current study's findings, it is believed that utilizing different inputs might alter fire risk estimation. Comparison of two indexes are given in Figure 5.1 and Figure 5.2 in both ECMWF data was utilized except that MEUS also incorporates wind speed and wind direction. On the other hand, FPI utilizes both of land use data and imagery. As can be seen in these figures, even though there were fire occurrences in Hatay and Kahramanmaraş which were shown by Figure 5.2, MEUS failed to represent fire risk for the same day.

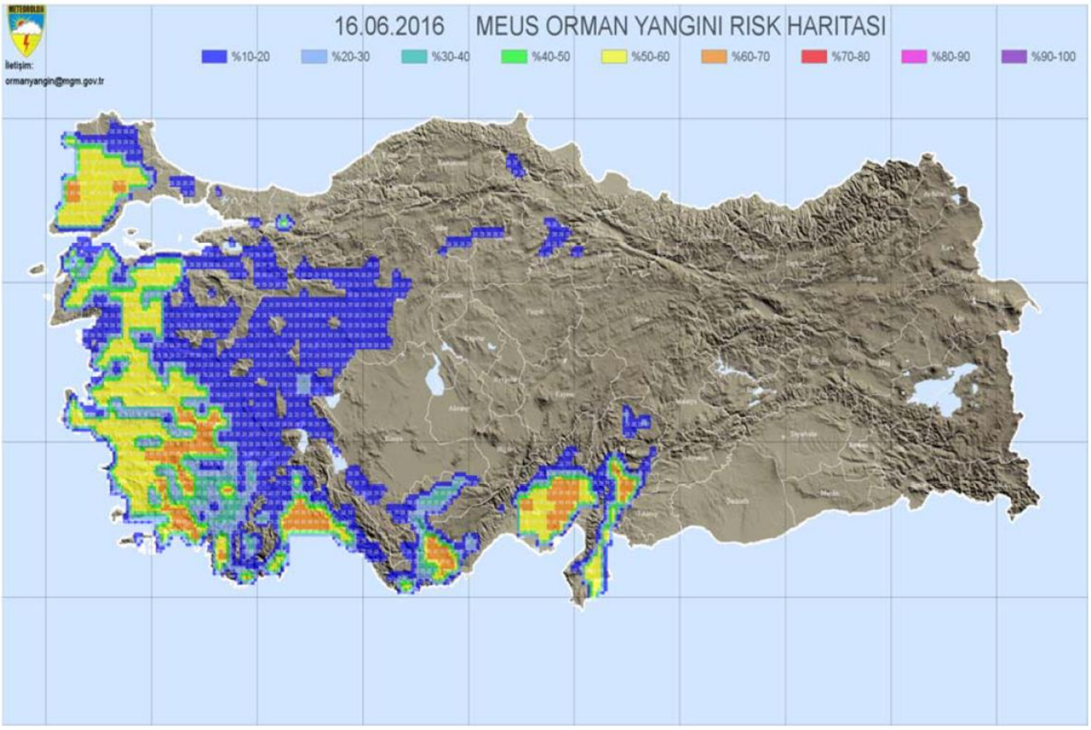

Figure 5.1 MEUS scores of 2016-06-16.

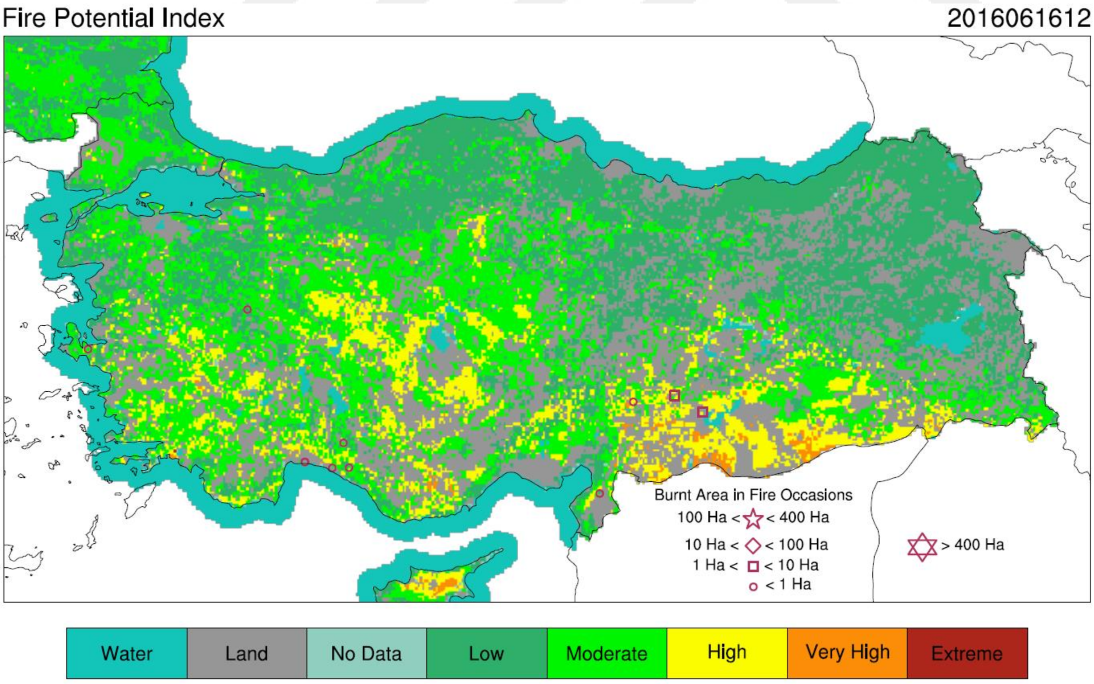

Figure 5.2 FPI scores and fire events in 2016-06-16.

Analyses in this study showed that coarse resolution is considered to be the limiting factor for the index's prediction skill. Even area of a grid point (0.04x0.04 degree) is bigger than the area burnt in most of the fire events. It is most likely that selected resolution causes a smoothing effect to where hotspots might occur. Smooth out of some local high and lows in NDVI values are possible due to interpolation. FPI could significantly benefit from the availability of a meteorological data which has a comparable resolution to satellite data. Meteorological input fields needed to be examined for possible biases which could alter FM_{10} values and consequently FPI scores. Coupling FPI with a high resolution numerical weather prediction model which is executed by the same land use data as the index might lead better estimation of fire potential since land cover significantly effects relative humidity and temperature due to varying albedo, roughness, and heat flux properties of the land. General Directorate of Meteorology in Turkey performs operational numerical weather prediction modelling. These outputs would be valuable inputs for FPI in the future research.

In the present study, fire occurrences in some particular cities show dramatic differences with their surrounding cities although there were no significant climatic differences. For instance, İstanbul is the most populated city of Turkey with more than 15 million people. Also, there were high number of fire occurrences in other big cities of Turkey such as İzmir, Bursa, and Antalya. As human activities are a major cause of ignition, the higher number of fire occurrences in these big cities are congruent with expectations. In this regard, it is believed that population density, relative area of forest interface, and relative area occupied by road and transportation networks should be part of fire risk analysis in the future examinations (Vilar, Camia, & San-Miguel-Ayanz, 2015).

Relative greenness estimation in this study was made by NDVI product of EUMETSAT MSG imagery. However, higher resolution imagery samples such as MODIS or LANDSAT should also be tested in the future studies in order to examine which one of these instruments provide more accurate results. Furthermore, application of Normalized Difference Water Index (NDWI) which is more sensitive to moisture content of vegetation can be better for demonstrating fire potential since NDVI relies on color of vegetation which change with deterioration of chlorophyll pigments (Huesca, Litago, Palacios-Orueta, Montes, Sebastián-López, & Escribano, 2009).

Utilizing a land cover data with more vegetation classes is also required since FPI is sensitive to variables of live fuel load, dead fuel load, and extinction moisture of dead vegetation. That could also increase the coverage where FPI is able to produce results.

Evaluation on FPI for an extended time period and frequency to better asses its prediction skills is needed. Especially evaluation of hourly FPI results with meteorological fields at that frequency could lead better estimates of fire potential. 12:00 UTC analysis fields of ECMWF was chosen since fire potential is regarded as its peak in the afternoon but fire records show there are many number of fires initiated early in the morning or night time. Advection of moisture and temperature are influential factors as much as diurnal radiation changes.

Verifying index results against observation of fuel moisture content in future studies can be a better approximation of index performance, since fire potential index does not have ignition inputs or relative fields might indicate the risk. It is believed that researchers and professionals in the field of forestry may benefit from routine and systematic observation of fuel moisture content.

There are some strengths of the present study. This study was the first one which conducted on operational fire risk estimation in Turkey. Moreover, although many studies on forest fire conducted by focusing on only a one region, mostly Antalya, and Muğla where most of the fire event occurs in Turkey, the present study is believed to contribute to existing knowledge by analyzing all parts of Turkey. Therefore, one can conclude that findings of this study provide a broader understanding.

In conclusion, although FPI is a valuable tool to assess fuel condition, inclusion of other parameters such as wind speed, slope, aspect, and human factor would help estimating fire risk more accurately.

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