December 4, 2011

Global Effects of Climate Change on Wildfire: Causal Relationships of Fire, the Natural Environment and Human Activities

Lindon N Pronto, *Pitzer College*

5. Global Effects of Climate Change on Wildfire: Causal Relationships of Fire, the Natural Environment, and Human Activities

Lindon Pronto

Climate change and human activity is significantly impacting the frequency and severity of wildfires across the globe. Although climate change and human population are the overarching factors affecting wildfires in the current dialogue, the issues are more complex and often not fully understood. These issues range from global temperature increases and severe drought cycles to the relatively new phenomenon of the wildland urban interface (WUI). This is the area where structures are integrated with or immediately surrounded by areas of moderate to high fire risk and are directly linked to fuel types and topographic features. Because climate change is such a highly politicized issue, there are generally limited governmental frameworks that enact policies that encourage a deeper understanding of the causal relationships between climate issues and population impacts on wildfire. While politicians debate whether climate change exists, scientists are showing us that it is producing real threats; some of these threats are the loss of life and property as a result of wildfire, as well as the critical economic impacts of suppressing these evermore frequently occurring, catastrophic fires.

Knowing exactly when fire regimes have changed over history and on a global scale is difficult, but there are some studies that have provided this information for specific geographic areas. Wathen (2011) reports one possible explanation for current fire regimes in the Sierra Nevada is the evidence of climate teleconnections over the past 1,800 years between the Sierra's and Greenland that suggested abruptly changing climate features. During that time period the onset of severe droughts in Nevada coincided with severe fires and erosion in Northern California. Wathen implies that some of these abrupt climate changes during the late Holocene are responsible for causing some mountain slopes to have vegetation types that were out of equilibrium to the climate conditions, subsequently leading to an increase in wildfire frequency and severity over time (Wathen). In more recent history, Dimitrakopoulos *et al*. (2011) concluded that there was a significant threshold change in Greece during the late 1970s during which more severe summer and annual drought cycles coupled with urbanization and higher rates of arson, led to spike in fire frequency and total annual area burned. Even so, perhaps one of the most recent areas to be added to the list of climate-induced fire regime changes was illuminated by Mack *et al.* (2011), in a revealing study about wildfire in the Arctic Tundra biome. As global temperatures rise, changing climatic conditions have introduced wildfire-induced carbon (C) releases in the Arctic tundra that have not been observed in many millennia. They found that these tundra fires have the potential to significantly amplify global warming through the release of concentrated C pools into the atmosphere—pools that in some cases are thousands of years old.

Recent science is showing us that climate change is the umbrella for shifting fire regimes around the globe. In Australia, fire intervals have historically been influenced by spatial variation in vegetation and landscape connectivity. Though areas of Australia differ from other landscapes, the effects of climate change may soon override these traditional fire regime norms that have been reliant on topographical features and vegetation connectivity (O'Donnell *et al.* 2011). In Portugal, fire activity has increased significantly while being exacerbated by fuel type, slope and elevation, and notably, proximity to roads and populated areas as well (Marques *et al.* 2011). In Alaska, rising global temperatures have caused seasonal changes in various ways particularly acute at higher latitudes. The summer of 2004 was the most severe fire season on record, largely attributed to a severe weather event, for which they determined climate change as being an underlying factor (Wendler *et al.* 2010).

The effects of climate change on fire can be further broken down to look at short and long term effects of fires on carbon stocks, or even how disease outbreaks have the potential to amplify fire severity such as Sudden Oak Death on the California coast (Metz *et al.* 2011). As forests contain the planet's largest terrestrial carbon stocks, wildfires, by burning forests, release a significant amount of this stored carbon into the atmosphere extremely rapidly. This release interrupts a longer cycle where carbon is sequestered by growing trees and then is finally rereleased during the decomposition of the vegetation. North and Hurteau (2011) expose how forest management practices can lessen the effects of wildfires on tree mortality and affect higher survivability during dangerous fires in Northern California.

Future models and predictions only point towards the development of further significant climatic conditions that are conducive of more frequent and extreme wildfires. In Brazil, based on future climate models concerning the Potential Fire Index (PFI), changes in vegetation composition are expected to greatly increase the magnitude of the PFI. Furthermore, climate conditions are expected to potentially extend the fire seasons as a result of longer drought periods especially in the Amazonia (Justino *et al.* 2010). Similarly in China, according to future models, fire danger, fire activity, area burned, and fire season duration are all expected to increase significantly over the next century. Xiao-rui *et al.* (2011) concluded that the above phenomena would in fact occur under two of four climate change scenarios outlined by the Intergovernmental Panel on Climate Change (IPCC) covering the period from 1991–2100.

Perhaps the issue that raises the most public concern and political dialogue is the issue of public safety, loss of property, and the costs of suppressing fires. This collection of papers hardly makes a dent in these important issues because it is the subject worthy of many volumes; this is due to the plethora of geographic technicalities such as climate and fuel type, accessibility, proximity to population, economies of scale and resource allocation, skill level and suppression resources available, technology…and the list goes on. Included are two papers that do focus less on field work or climate models. First is a paper by Cova *et al.* (2011) which maps some of the dangers of increased wildfire prospects up against the ever and rapidly expanding wildland urban interface (WUI). The threat analyzed here is the limited access routes, which make immediate egress in the event of a severe wildfire threat, an additional hazard for these communities. Finally, is a paper that deals with solutions for a forest management plan that takes small communities located deep within the WUI into account as they are often left out of the equation for reasons largely to do with economies of scale. This approach works to combine forest management, energy acquisition, sustainable design, and community participation to address not just the threat of wildfires, but the rest of the challenges that face these types of communities (Yablecki *et al.* 2011). These last two examples are immediate issues of public safety and strong constructive suggestions for future policy building and regulatory foresight for population expansion into fire-prone areas.

* * *

Following in the footsteps of my father, at the age of 17, I completed my basic training as a wildland firefighter. In the following summer of 2007 I reported to my duty station as a newly hired "professional" federal firefighter in the USDA Forest Service in northern California. My lifelong relationship to fire might have begun when I tripped and fell in one as small child, but it certainly has developed over many years of fuel treatment and fire prevention projects on my family's property, through countless dinner conversations, and eventually it led to me dedicating a significant part of my life to protecting forests and communities and combating fires. Since, I have had the opportunity to fight fires in six states and have the pleasure of sharing a common passion with my father, with the ability to tap into his over 30 years of experience. It has fascinated me to open my eyes to the global phenomenon of wildfire and climatology, deviating away from my narrowed understanding centered on fire characteristics and fire management practices in the western United States. It was exciting for me to read studies about fires I fought, augmenting my memories of adrenaline and gritty backbreaking labor, with the scientific effects of immediate carbon release in the atmosphere, or the subsequent effects of ash on stream ecosystems.

In this selection of articles I have attempted to first show the effects of climate conditions on wildfires from past examples to future daunting models of predicted wildfire potential. This general scientific foundation is intended to convey the broader sense of increasing wildfire frequency and severity as it is rooted in changing climatic conditions shown on a larger geographic scale. Secondly, I chose some studies to focus more on specific issues within this dialogue such as carbon stock release or the effect of disease on fire severity. Finally I wanted to end with two papers that begin to address the dangers of population centers within the WUI as well as looking at a multifaceted solutions based approach to addressing fire, fuels management, energy acquisition, and carbon emissions as a cluster issue. My overall goal was to represent the issue on a global scale, though admittedly the majority of the focus is placed on North America as there was a higher availability in studies in the United States and Canada. Had I had more time, I would have also liked to include more studies from South America, parts of Africa and especially Australia and Russia—where wildfire events have been particularly catastrophic in recent years.

Impact of Drought on Wildland Fires in Greece: Implications of Climate Change?

A spike in wildfire frequency and amount of area burned in the past decades has been increasingly attributed to factors induced by climate change. Though shifting wildfire regimes are strongly affected by more direct human actions, such as increased rates of arson or the effects of urbanization on rural land use, a study by Dimitrakopoulos et al. (2011), chose to focus on the impacts of drought on wildfire activity in the country of Greece. The study analyzed data from weather stations representing all of Greece over the 37 year period between 1961 and 1997. This time period was chosen because it presented the greatest uninterrupted time interval in the available data. The study sought to prove that an increase in severity of annual and summer droughts has resulted in higher rates of wildfires and the total area burned. The study concluded that there was a statistically significant increase in fire activity and a positive correlation between it and annual drought episodes. It also showed that fire activity has increased significantly since 1978, and that drought played a larger role on fire activity in the more humid and cooler regions of Greece.

The area studied groups together 17 prefectures into five geographic regions denoted as Northern, Western, Central, Eastern, and Southern Greece. The prefectures used in the study were chosen for the availability of 37 years of data from official meteorological stations. This study represented drought by the Standard Precipitation Index (SPI) and measured the two main phenomena of annual drought (expressed as SPI12) and summer drought (expressed as SPI6). The study identified all prefectures under respective climate types based on precipitation levels and were expressed as "semi-dry, semi-wet, and wet." Wildfire activity, characterized by number of fires and area burned, was also tracked in all 17 prefectures. Aside from applying SPI values to the entire 37 year period, the study was broken down into two separate sub-periods of 1961–1977 and 1978–1997 for data analysis purposes. Dimitrakopoulos et al. were able to detect several fire regime shifts using the extant data with Change Point Analyzing software; by observing the shifts, the data allowed them to determine that a threshold change occurred in 1977. This was significant for analyzing all data during the second sub-period from 1978 to 1997.

The results confirmed the trend that wildfires had increased steadily from 1961 to 1997 in all areas of Greece. More specifically the Northern, Southern and Western areas exhibited a stronger more significant change than the other two regions. Moreover, there was a significantly higher level of fire activity in the second sub-period, as well as a notable increase in area burned for that period as compared to the earlier sub-period pre 1978. Interestingly, the increased rate of fire occurrences between all the regions was not consistent with the area burned geographically, which depended on the region (climate).

By following the SPI12 and SPI6 values, it was determined that both annual and summer drought episodes increased significantly after 1977 for both the Northern and Western regions. Excluding Eastern Greece, all other areas showed a strong positive correlation between fire occurrence and drought episodes during the entire 37 year period. More specifically, Southern and Central Greece (historically exhibiting the highest level of fire activity) did not correlate with the SPI12 value, indicating that it was most heavily influenced by summer droughts (SPI6) alone. While the different regions correlated with both one another and with summer and annual droughts in different ways, the overall effect was that an increase in starts (new fires) geographically mirrored the greater area burned in the cooler more humid climates when more frequent droughts were present.

The overall trends show that between 1961 and 1997, the mean area burned almost quadrupled in Northern Greece nearly tripling in the other districts, while the number of fires almost doubled in Northern and Western Greece. These implications for a global climate change are echoed by increased fire activity in other parts of Europe as well as the rest of the world. In this study, it is apparent that in Central and Southern Greece (warmer and drier) drought episodes during the summer were most detrimental to fire activity while the other regions exhibited increased fire activity when the annual precipitation levels fell, inducing increased fire behavior in response to lower fuel moistures etc.

One interesting contradiction in the results displayed that between the two sub-periods, drought and fire occurrence correlated more significantly leading up to 1978, while a stronger correlation occurred between drought and area burned in the second sub-period after 1977. Dimitrakopoulos et al. offer the following explanation for why this is so: The contradiction lies in the actual cause of individual fires. During the 1961–1977 period, rural Greece was much more heavily populated and the most common cause of fires was negligence. By the late 1970s, urbanization redistributed the population, effecting rural land use, and apparently resulting in a dramatic increase in arson cases. Furthermore, the common denominator for large fires besides high temperature and low Dead Fuel Moisture Content is wind; arson fires can account for large area burned due to their timing with wind.

In conclusion, during the 37 year period, there was a positive correlation with increase of fire activity and annual drought episodes. In Northern and Western Greece alone, fire activity was influenced by both annual and summer drought episodes (which increased after 1977) as opposed to only the summer ones. A possible result of climate change marked a period of prolonged drought in Greece after 1977, which consequently matches a significant increase in the number of fires and area burned during the second period. Overall, the first sub-period 1961–1977 was characterized by its number of fire occurrences to drought correlation, whereas the second sub-period

1978–1997 exhibited a higher correlation to drought and total area burned. Finally, the effects of climate change (increased drought episodes) had a more profound effect on fire activity in wetter colder regions of Greece where historically fire occurrence and area burned was lower. Increased drought episodes have visually impacted wildfire activity in Greece, while current climate change models suggest that further similar trends will, in the future, result in more severe and frequent fires in the Mediterranean region.

Future Impacts of Climate Change on Forest Fire Danger in Northeastern China

As a result of global climate change, many areas around the world will be more prone to increased wildfire activity. Wildfires will become more frequent, burn more intensely, and will burn larger areas; additionally, fire seasons (time periods during which fire is most active) will in many cases be observed for longer durations annually. In a study by Xiao-rui et al. (2011), projections of climate change effects on wildfire danger in the boreal forests of northeastern China were made for the remainder of the century. These future effects were weighed against and validated by historical regional climate data for the baseline period of 1961–1990. The purpose of the study was to prove that fire danger, fire activity, area burned, and fire season duration would all increase significantly over the next century. Xiao-rui et al. concluded that the above phenomena would in fact occur under two of four climate change scenarios outlined by the Intergovernmental Panel on Climate Change (IPCC) covering the period from 1991–2100.

The area chosen for this study encompassed three general areas of boreal forest in northeastern China, accounting for about 37% of the total forested area in the country. These areas were the Daxing'an mountains, the Xiaoxing'an mountains, and the Changbai Mountain forest region. The overall terrain consists of plains in the central area and mountains in the east and west. The study used a validation period of 30 years based on data available from the China Meteorological Data and Sharing Network, where 107 weather stations were located within the study area. Xiao-rui et al. chose to use the Canadian Forest Fire Weather Index (FWI) System to analyze changes to fire danger and the fire season for future periods under IPCC Special Report on Emission Scenarios (SRES) models A2 and B2. The FWI is calculated on the basis of six factors that shape the effect of fuel moisture and wind on fire behavior. The two models used from the IPCC Special Report on Emission Scenarios demonstrate an estimated global average surface temperature warming of 1.4–5.4°C between now and 2100. Both A2 and B2 fall under the "regionalization" scenario (heterogeneous world) where A2 is global temperature increase under a projected approach of regionally orientated economic development, while B2 is a projected approach of localized efforts of environmental sustainability (IPCC, 2007). Additionally projections were made for the overall time periods of a) 2020s, b) 2050s, and c) 2080s; sub-periods examined changes by individual decade. Data sets were illustrated under both A2 and B2 scenarios.

For the study area, two peak times took place during each fire season. First, an approximately three-quarter percent of annual fires occurred during the spring season from March to May, while in the fall period in October, fewer than 10% occurred but accounted for nearly one-quarter of the annual area burned. As a result of these findings, the study was adjusted to account for the two separate fire season peaks under both the A2 and B2 IPCC scenarios. The overall historical trend of the Fire Weather Index (FWI) was high in the spring, and relatively low in autumn; this correlates to future FWI projections, with a notable spike in the 2080s. Geographically, heightened FWI and fire activity were predicted for most of the region especially in the southeast, while few and temporary decreases in high risk fire days were observed. The east-central region exhibited the overall highest FWI values under both models by 2080. Also by

2080, the potential burned areas under scenario A2 are expected to increase by 10% in the spring peak and by 23% in autumn, while under B2 an increase of 18% and 35% respectively, was predicted. One of the more critical effects of global warming is the number of days of fire seasons. This study suggests that for northeastern China, the number of days that exhibit high or extreme fire danger may by 2080 increase by more than 20 days in the Daxing'an Mountains and Xiaoxing'an Mountains, and 41–60 days in the Changbai Mountain region. This trend is expected to be most obvious in the southeast and northwest regions.

The three most important factors that drive fire behavior are fuel, weather, and topography. An important element that was not accounted for in this study is the potential impact of 100 years of climate change on fuel type. The authors of this study suggest that in order to gain a clearer understanding for developing a fire management strategy, it is important that future research focus on incorporating additional effects of long-term climate change on successional vegetation changes in burned areas or areas of temperature induced plant regime shifts. In conclusion, Xiao-rui et al. contend that under the temperature increases outlined by the IPCC models, the threat of wildfires will increase, a greater area will be burned, and certain geographic areas will exhibit significantly lengthened annual periods of high FWI values during the peak spring and autumn fire season. The authors hope that this study can aide in shaping future fire management strategy and practice through knowledge of these future climate scenarios, such as through improving elements like prescribed burning and initial attack-phase fire suppression responses.

Climatology of Alaskan Wildfires with Special Emphasis on the Extreme Year of 2004

As global temperatures rise, the seasons shift in various ways depending on their latitude. For many areas such as Interior Alaska, the annual dry season has become longer and surface fuels have consequently become drier; this has led to an increase of wildfire frequency and severity. Wendler et al. (2010) conducted a 55 year analysis of the various conditions conducive for and associated with, predominantly lightning induced fires in Interior Alaska. With a special emphasis on the extreme year of 2004, the authors examined data for lightning and fire ignition, number of fires versus area burned, and air quality and composition. Special emphasis was placed on the year 2004 where specific fire and climate data, weather, particulate matter, and carbon monoxide concentration, were all examined within the broader context of the whole 55 year data set. They determined that 2004 was the worst fire season on record (in terms of area burned) and that there has been an overall trend in increased wildfire severity and occurrence. Although the unique weather patterns for the summer of 2004 were attributed to the severity of the year, they did show that climate change has been an underlying factor. Furthermore they demonstrated that there were four major fire seasons burning an area greater than 10,000 km^2 in the last 27 years, as opposed to only two in the previous 28 years.

The authors examined the Palmer Drought Severity Index and the Canadian Drought Code, against both the number of wildfires and the area burned in order to find any significant correlations. Lightning-caused fire data were collected by the Alaska Lightning Detection Network operated by the Bureau of Land Management and the Alaska Fire Service. These data were then used to show the spatial distribution of the lightning strikes, the mean monthly strike count, and the diurnal variation of the strikes. Additionally, temperatures and precipitation patterns were evaluated in terms of lightning activity levels; they found that as temperature increased, so did the lightning activity.

General historical data from 1955–2009 showing number of fires and area burned were retrieved from the Alaska Fire Service, while very detailed data from the 2004 fire season were compiled. On average, 3,775 km^2 burn annually in Alaska, of which about 90%

occurs within the interior of the state as bounded by the Brooks Range in the north, and the Alaska Range in the south. During the 55 year study period, about 93% of fires were started by an average of 32,000 lightning strikes per year. Statistical analyses showed a correlation coefficient of r=0.67 in the ratio of lightning strikes to resulting wildfires, with an estimate one fire per every 600 strikes. Furthermore this relationship is much higher when positive and negative strikes are evaluated independently of overall fire starts. Positive down-strikes occurring during dry conditions are more infrequent than negative down-strikes which are usually accompanied by precipitation. Despite the lower frequency of positive down-strikes, they are four times more likely to result in a fire. The vast majority of lightning occurs during the months of June and July.

In the summer of 2004, a record 27,200 km^2 burned (well over 6,700,000 acres), or an area greater than any 6 of the smallest states in the US. It was in this year that many areas around the state set record high temperatures. Additionally, and what is believed responsible for the extremity of the fires in 2004, is the unique weather patterns that occurred. Anticyclonic conditions resulted in unusually clear skies and the third driest summer on record. For calculating the correlation of climate conditions and fire occurrence, the authors found that the Canadian Drought Code (CDC) was more effective than the more commonly used Palmer Drought Severity Index (PDSI). Beginning with below normal snowpack in the spring, a semi-permanent upper-ridge followed with above normal temperatures and below normal rainfall. During two distinct periods of 4 weeks and 3 weeks fires burned an area of 16, 200km^2 and 8,000km^2, respectively.

Air quality during this time period deteriorated severely, dramatically reducing visibility and causing significant health risks to the population. Wendler et al. chose to focus on visibility, particulate matter, carbon monoxide (CO) concentration, and radiative fluxes. They found that during the worst of one of the more severe smoke events, visibility was <1/4 mile, fine particle matter exceeded 1,000 μg/m^3, while CO concentration levels reached a value of 10.3 ppm; maximum levels prior to smoke never exceeded 1.0 ppm. The transmissivity was calculated as the percent of outside solar radiation that reached the surface as direct solar radiation. During the smoke events, less than 10% of direct radiation occurred. When the CO concentration level and the particulate matter were correlated, there was an overall variance of 72% and 80% during the two major burn periods; they concluded that a relative abundance of CO in relation to particle matter is to be expected for the older smoke of the second period.

Due to the increase in temperature of 1°C in Alaska over the past half century, more frequent and severe wildfire events can be attributed to the latter increase, even when they start nearly exclusively from natural causes as only opposed to increasing human activities in wildland areas. For example, this study shows that during the first half of the study period, 6 years with mean summer temperatures above 16°C occur, while for the second half, this occurred nine times. Similarly, severe fire seasons (>10,000 km^2 burned) increased from 2 to 4 events from the first 28 years to the second 27 years. Furthermore wildfire events where >5,000 km^2 burned, increased from three to eight events. This pattern can be contributed to an overall trend of quick or prolonged drying of the surface fuels and soils that increase the likelihood of ignition from a lightning strike. This study synthesizes data to try and recognize conditions for severe fire events and thereby perhaps aide in predicting efforts needed by fire suppression forces in near-future situations; however it does admit that predicting the severity and length of future fires seasons is largely speculative as it can only be based on previous climate patterns of the past 30 years.

Characterization of Wildfires in Portugal

An increase in forest fires in Portugal supports climate change models suggesting that the two phenomena are linked. In recent decades the occurrence of wildfires, their severity, and the area burned, have all increased. In an effort to help in formulating a fire management plan, Marques *et al.* (2011) conducted a study to characterize wildfires in Portugal. The object of the study was to demonstrate trends in fire activity and examine how fuel type, fuel load, elevation, and socioeconomic factors have bearing on fire severity. What the authors found was that fire behaved selectively based on fuel type, slope and elevation, and proximity to roads and populated areas. Furthermore, they established that shrubs displayed the most significant fire activity potential, especially at higher elevations on slopes greater than 5% and further away from socioeconomic influences.

Using historical fire information data, a 33-year-long period from 1975 to 2007 was used as a basis for observing trends in fire occurrence, proximity, and severity. Burned area mapping was established through the use of high-resolution remote sensing data by the Remote Sensing Laboratory of Instituto Superior de Agronomia. The study was broken down into three separate 5 year sub-periods (1987–1991, 1990–1994, and 2000–2004) in an attempt to minimize the effects of land cover changes over time. From land cover maps the authors were able to identify fuel types and distribution. In addition to devising 10 classes of cover types for the purpose of the study, Marques *et al.* identified altitude, slope, proximity to roads, and population density as four additional variables for modeling purposes. Altitude and slope data were obtained from the country's digital terrain model (DTM); GIS overlays from the Instituto Nacional de Estatística provided data on road proximities and population density. Relationships between Ecological and socioeconomic variability and fire occurrences during the three sub-periods were largely based on statistical models.

Over the 33 year period fire perimeter data show that there were 35,194 wildfires which were greater than 5 ha in size. Area burned per year ranged from 15,500 ha in 1977 to 440,000 ha in 2003, where a single fire was responsible for 58,000 ha alone. The first sub-period (1987–1991) had 7,672 starts; the second sub-period (1990–1994) exhibited significantly calmer fire activity with 5,703 starts. The third and final sub-period (2000–2004), was characterized by a significant increase in fire occurrence and size; while the period had 7,383 starts, the area burned was over 43% greater than the first sub-period and 182% for the second sub-period respectively. Most notably the final period exhibited the occurrence of four very large fires being greater than 20,000 ha each in size. There were no fires greater than 20,000 ha during the first 25 years of data.

Weighted generalized linear models (WGLM) proved that the number one high risk fuel was shrubs, followed by mixed stands, softwoods and hardwoods; individual species added variance based on fuel loading, resin, and foliage essential oil content. Marques *et al.* also observed that fires occurred more frequently at higher elevations, which was attributed to higher lightning activity levels (LAL) and escaped pastoral burns. An additional factor found more generally at higher elevations was that of greater slope which contributed to faster rate of spread. In populated areas in Portugal, although human activity is the number one cause of wildfires, their proximity to roads and population centers allows for a very quick response time from firefighters who are often able to extinguish the fires when they are still small. When fires occurred away from populated areas where there was limited or no access, data show that these fires tend to become very large, especially in mountainous areas where slope accelerates rate of spread. There was a positive correlation between distance from populated areas and the area burned.

Through this study, Marques *et al.* were able to characterize wildfire in Portugal with special attention to socioeconomic influences, fuel type, and landscape specific variability. The technique which made this approach possible was the use of weighted generalized linear models which highlighted the relationships of ecological and socioeconomic factors. This study is intended to provide a starting point for policy makers to develop an appropriate and effective fire management plan that is current with wildfire activity trends and congruent with the possible effects of climate change. It provides a context for developing fire prevention practices and policies; furthermore, it suggests continued work in this subject area to translate these results into functioning fire prevention and suppression models for the country of Portugal.

Carbon Loss from an Unprecedented Arctic Tundra Wildfire

As increased frequency and severity of wildfires in historically fire-prone areas pose one set of threats to our ever-more concerning climate situation, scientists have identified a new threat to rising global atmospheric CO_2 levels. Not since the early Holocene epoch has there been any significant wildfire activity or the presence of typical fire regimes within the Arctic tundra biome. As global temperatures rise, changing climatic conditions have introduced wildfire-induced carbon (C) releases in the Arctic tundra that have not been observed in many millennia (perhaps 10,000 years or more). Mack *et al.* (2011) examined the Anaktuvuk River fire that burned 1,039 km^2 of Arctic tundra on the North Slope of the Brooks Range in Alaska, USA, in 2007; this single fire burned more than double the cumulative area burned in the region over the past half-century. They concluded that the C released from this one fire supports the hypothesis that tundra fires have the potential to significantly amplify global warming through the release of concentrated C pools into the atmosphere that in some cases are thousands of years old.

Mack *et al.* report that the Anaktuvuk River fire burned 1,039 km^2 removing $2{,}016 \pm 435$ g C m^{-2} and 64 g N m^{-2} (or about 400 years of N accumulation) from the ecosystem, an amount they say is two orders of magnitude larger than annual net C exchange in undisturbed tundra. Furthermore they report that “the approximately 2.1 teragrams of C [released] into the atmosphere, was an amount similar in magnitude to the annual net C sink for the entire Arctic tundra biome averaged over the last quarter of the twentieth century." Approximately 60% of this C loss was from soil organic matter. Radiocarbon dating of residual soil layers showed the maximum age of soil C that was lost in the fire, was 50 years old.

The study area was underlain by permafrost and had a mean annual temperature of –10°C and an average yearly precipitation of 30 cm. The pre-fire vegetation composition of the study area was 54% moist acidic tundra (MAT), 15% moist non-acidic tundra, and 30% shrubland. The study focused on the MAT classification because of its wide distribution and because it had a higher immediate survivability than the other fuel types and therefore was able to provided a benchmark of pre-fire soil organic matter depth and plant biomass. Eleven MAT sites outside the burn area and 20 MAT sites within the burn were sampled. Sites were tested in order to compare pre-fire soil organic layer depth and depth versus bulk density, C or N concentrations, and to determine the radiocarbon date of the post-fire soil surface to see whether the fire burned into old and likely irreplaceable soil C pools. The objective was to observe the soil C and N content approximated at pre and post-fire locations to determine the emissions of the particular fire event and to put the results in context with a broader understanding of tundra biome historical norms and characteristics of the climate.

Independent of the transfer of C from the tundra soils to the atmosphere is the threat that any significant disturbances by wildfire have the potential to change local thresholds and alter the ecosystems structure and function through the alteration of surface reflectance (albedo) and energy balance of landscapes that are underlain by permafrost. For example, lake sediment cores showed that there was no observable wildfire activity within the study area over the past 5,000 years. A wildfire event of the magnitude of the Anaktuvuk River fire, has the potential to destabilize the underlying permafrost allowing it to release additional C into the atmosphere during the subsequent decomposition process (as a result of exposure), and adding significant potential for contributing to positive feedback to high-latitude warming. An additional important consideration are the increased concentrations of C stored at increased depths in peat soils, for when drying does occur in this fuel type, the fire doesn't only burn in a greater radius but can do more vertical damage as well in the semi-combustible soils; an image of the burn scar conveys this phenomenon very well. In this study in particular, though there were areas that had a soil depth range of 12.3–43.3 cm, the maximum burn scar areas were no greater than 15 cm in depth.

Mack *et al.* conclude that even a single surficially burning wildfire in the Arctic tundra biome can offset or even reverse biome-scale C uptake. Furthermore, C released into the atmosphere from fire occurs at a rate of 30–50 times greater than C release through natural decomposition mechanism such as, for example, stimulated soil organic matter decomposition from a 5°C increase in mean annual temperature. One possible implication raised by the authors is that changing local thresholds may lead to succession patterns that replace the current biome organic soil and vegetation composition with more shrubs. Such a shift would have the potential to …"trigger additional positive feedbacks to climate warming because shrub-dominated ecosystems have higher productivity and plant biomass offset by lower soil C stocks." Although scientific knowledge and experience with the effects of fire in the Arctic tundra biome are very limited, an increase in this phenomenon has led studies such as this one to conclude that the possible near-future effects of fire in the Arctic can have catastrophic implications for atmospheric carbon levels as well as terrestrial carbon capturing and storing. As seen in the last 20 years, this dangerous positive feedback system of climate change is accentuated—from the high latitude warming resulting in melting snowpack and permafrost, retreating sea ice, to the drying-induced fire having varying consequences from albedo loss to instantaneous mass C releases from age old stocks.

Lindon Pronto

High-severity Wildfire Effects on Carbon Stocks and Emissions in Fuels Treated and Untreated Forest

Forests contain the planet's largest terrestrial carbon stocks. Wildfires, by burning forests, release a significant amount of this stored carbon into the atmosphere extremely rapidly. This release interrupts a longer cycle where carbon is sequestered by growing trees and then is finally rereleased during the decomposition of the vegetation. Under forest management practices, forests have in many places been "treated" to lessen the effects of wildfires on tree mortality and to be better positioned to have higher survival during dangerous fires. In a study by North and Hurteau (2011), the short term effects of wildfire on carbon stocks were reviewed using field measurements, comparing treated and untreated forest areas in recent burn scars. The authors found that carbon emissions (during a fire) were more than double in treated areas. They further discovered that when the carbon release from the treating process was added to the emissions of wildfire in those same treated areas, the carbon emissions were significantly higher than untreated burned areas (93% tree mortality rate). This however is over a short time period, and that other studies suggest carbon emissions could be up to three times higher over an extended time of natural decomposition as opposed to the instantaneous carbon release induced by wildfire.

This study collected data from 12 fire sites in California (Region 5), mostly from recent burn scars in the northern Sierra Nevada. The area was chosen for its extensive use of fuels treatment practices by the U.S. Forest Service, which provided the necessary comparison basis for evaluating carbon emissions for treated and untreated fuels during wildfire events. The objective of this comparison was to assess differences in (1) carbon stocks, (2) carbon loss from treatments and wildfire, and (3) tree survival, mortality, and changes in live tree sizes and species composition. The selection areas were constrained to areas that fell under the practice of 'thin from below' prescription, through the use of machinery which creates 'machine piles' of slash (often discarded from logging operations) which are burned during favorable weather conditions. The study identified 20 treatment areas that had been treated within the past 5 years; the dominant fuel type was mixed-conifer. Areas where fuel treated projects had not been concluded by the onset of the wildfire (such as unburned machine piles), were excluded from the data.

Using the boundary of fuels treatment projects, 3–6 plots of 0.05 ha for ≥5 cm diameter at breast height (dbh) and 0.1 ha for trees ≥50cm dbh, were selected in both burned/treated and burned/untreated areas, usually measured within 200m from each other for consistency in fuel characteristics. Through a variety of methods, carbon content in treated and untreated stands was calculated as accurately as possible to best represent (estimate) carbon content before the fire to be paired with actual results after the fire. The study assumed that carbon concentration was 50% in woody material and 37% in duff and litter. It was determined that carbon emissions of the fire were 11% of the total stored carbon in treated areas while 25% in untreated areas. North and Hurteau found that on average, fuel treatment removed about 34% of total stored carbon. Additionally tree mortality as a result of the fire was on average 43% and 97% in treated and untreated stands, respectively. The authors determined that if the carbon emitted during the process of treating fuels (i.e. prescribed fire) were added to the wildfire emissions, the treated/burned fuels produced a higher mean net carbon loss (80.2Mg C ha 1) than the untreated/burned fuels (67.8Mg C ha 1). However, this is in the context of short term carbon releases, and the same fuels decomposing over an extended period of time will generally produce significantly higher overall carbon emissions. However, if logging operations were used in the treatment process, a part of that carbon store could be subtracted from the overall emissions for that area.

In treated areas wildfire intensity decreased significantly, and carbon loss and tree mortality was lower. Although the authors found that 75% of the forest carbon stocks still remained onsite after severe wildfires, up to 70% of ecosystem carbon became decomposing pools in untreated areas, with only 19% in treated areas. The overall effect was that regardless of fire severity, carbon sinks become carbon pools until the carbon sequestering of the re-growth process became greater than the carbon emissions from the decomposing stocks in the following decades.

In summary, North and Hurteau found that treated areas significantly reduced fire severity and consequent mortality and reduced the carbon emissions during the fire event specifically. However, when the emissions from the treatment process were added to those of the fire, carbon emissions were significantly higher than those produced by severe fire in untreated stands (logging excluded). This study was not intended to be extrapolated to entire fire perimeters due to the extremely variable burn conditions of these different fires; the pairs (treated/untreated) were matched to very small areas of each respective burn. Overall, fuels treatment was found to likely shorten the time until carbon was re-sequestered by stand growth, due to higher survivability. This study suggests that fuels treatment projects that reduce wildfire intensity, successfully reduce carbon emissions during wildfire events and over the long term, by reducing the amount of carbon emitting stocks in long term decomposing stages.

Interacting Disturbances: Wildfire Severity Affected by Stage of Forest Disease Invasion

The presence of disease in wildfire prone areas has generated the assumption that increased disease outbreaks result in increased fire severity. Studies suggest that this relationship is in fact more complex and empirical data show that fuel loading and disease stage are more indicative than merely the presence of disease alone. One challenge when evaluating the effects of disease on fire severity is that often no pre-fire data exist in infected areas, so mapping post-fire characteristics that are induced by pre-fire forest conditions becomes speculative. Metz *et al.* (2011) had the unique opportunity to observe the effects of Sudden Oak Death (SOD) on wildfire severity on the California Central Coast. They examined results from the 2008 Basin Complex [fire] that had a perimeter encompassing 98 of the 280 plots established in 2006 and 2007 to monitor the effects of SOD on the forest. They found that there was generally minimal difference in fire severity in SOD infested and non-infested plots, except that the more concentrated dead fuel loading on the ground in SOD areas did increase the effects of fire on soil characteristics. Furthermore, the minor effect of SOD on fire severity was more observable in areas that were in the early stages of SOD infections because of the high presence of dead leaves and small diameter branches in the canopy that had not yet fallen to the understory. These "light flashy fuels" can be very volatile when ignited and can increase fire severity.

Sudden Oak Death is an infectious pathogen that is increasingly affecting California coastal forests with high rates of tree mortality, resulting in increased dead fuel loading and altering overall fuel type characteristics; this has varied implications for forest management practices and wildland fire suppression tactics. An extensive network of forest monitoring plots in Big Sur California was able to provide more clarity to these causal uncertainties. The 280 forest monitoring plots were selected as 500-m^2 areas, wherein a variety of measurements and classifications were made such as vegetation basal areas (from diameter at breast height) to determine fuel loading, and estimated time since death and whether infection induced or not. The network of plots was established in 2006 and 2007. In 2008 the Basin Complex burned through 35% of the study area, and 61 of the plots were measured immediately after the fire in order to compile accurate data for the pre and post-fire stages. The purpose of the comparison was to answer the following questions: (1) Did pre-fire fuel loads vary among areas that differ in pathogen presence or impacts? (2) Was burn severity higher in areas that had previously experienced higher SOD mortality? (3)Does the stage of disease progression influence burn severity because of changes in fuels through time?

The forest plots were defined under two fuel types (redwood–tanoak and mixed evergreen) and were measured on pre and post-fire occasions to determine disease incidence, mortality, amount of coarse woody debris, and other physical and biological fuel characteristics. First, Mann-Whitney U tests were used on both fuel types to determine the composite burn index (CBI) in both pathogen infested and non infested plots. Secondly, further sequences of tests were performed to find, for example, if CBI increased in areas with higher basal areas of standing dead trees in infected plots; through this process the authors set about to determine some of the relationships of SOD induced fuel characteristics on wildfire severity. The 2006–2007 plot mortality data were used as a proxy for observing an increase of new host mortality, as well as to observe the progression of longer term SOD effects (downed logs) on fuel characteristics and subsequent fire severity.

The results indicated a variety of both anticipated general assumptions as well as slightly more unforeseen overall causal relationships to fire severity. First, Metz *et al*. found that standing basal area and downed log volume were significantly higher in pathogen infested plots; however, there was no significant difference in abundance of live or dead non-host species between infested and non-infested plot areas. Second, despite the increase in dead woody material of SOD-associated species, no significant increase in burn severity between infested and uninfested plots was observed. Third, the authors found that it was more constructive to evaluate the relationships between burn severity and fuel abundance when two categories were created; one for recent host mortality and one representing an older SOD presence. Recent host mortality is characterized by more fine dead fuels, while longer term infection is observed by more downed heavy fuels (logs). Overall burn severity had a positive linear correlation to higher fuel loadings, as opposed to the presence of the pathogen alone; presence of the pathogen was not indicative of the overall fuel loading. However, one positive linear correlation was found—that higher standing basal areas and downed log volumes in infested plots resulted in increased soil burn severity. Furthermore, it can be assumed that elevated soil burn severity has other implications such as post-fire soil and ash erosion effects on watersheds; however these were not explored in this study. Although SOD mortality does affect a portion of these forests, a significant importance for host fuel abundance in determining burn severity, was not found when infested and uninfested plots were compared.

A similar phenomena to SOD, is the bark beetle outbreaks in many other western forests that also results in areas of high tree mortality. For both these instances it has been widely assumed that there is a positive correlation between tree mortality and fire severity. For both these instances, we now have empirical results that suggest otherwise. This study is consistent with similar studies that suggest perhaps the most significant contributing trait of tree mortality to fire severity is the relationship of time from disease or pest outbreak to time of fire occurrence. In conclusion, Metz *et al.* cautioned that fire severity was not consistent throughout, due to the large variance in terrain, fuel availability, and weather characteristics at the time of the fire across all of their plots. Concerns that tree mortality significantly influences fire severity are still valid, as geographic areas not explicitly covered by this study can contain a wide variety of species, topographical feature, temperature ranges, and humidity gradients. Nevertheless, this study provides a rare data set for pre and post-fire forest characteristics in SOD infested areas. Further research in this area may be helpful in guiding management and policy decisions for addressing SOD and fire hazards in California forests.

Lindon Pronto

Mapping Wildfire Evacuation Vulnerability in the Western US: the Limits of Infrastructure

In recent decades wildfire severity and occurrence has increased significantly due to a combination of climate change factors such as drought cycles, and population densities in fire prone areas. An increasing point of concern is the emergence of population centers within the wildland urban interface (WUI). This is the area where structures are integrated with or immediately surrounded by areas of moderate to high fire risk and are directly linked to fuel types and topographic features. When population centers in these areas have limited access routes, immediate egress in the event of a severe wildfire threat, becomes an additional hazard for these communities. Cova *et al.* (2011), focused on identifying some of these high risk communities in the eleven western states. The authors found that there was an inordinate quantity of high risk, densely populated communities with three or fewer evacuation routes in southern California as compared with the rest of the western United States. They imply that more attention should be paid during the planning and development of future communities in WUI areas, as well as taking certain fuels treatment measures to address safety in extant high risk WUI areas.

Climate conditions are increasingly blamed for an increase in wildfire severity and occurrence which has resulted in a high loss of structures and property damage over the past couple of decades. Furthermore, there are an estimated 12.5 million homes in what is considered to be the high risk, fire prone, wildland urban interface (WUI) in the western United States. Many communities are situated in the WUI but are not safely suited or adequately designed for a scenario in which an immediate, mass evacuation would be warranted due to a sudden severe threat of an approaching wildfire. This study projects a worst case scenario where most of a communities' population is at home (such as during night hours), and evaluates the number of egress routes (supply) against the number of households reliant upon them (demand). Cova *et al.* evaluated the eleven western states of AZ, CA, CO, ID, MT, NM, NV, OR, UT, WA, and WY, but divided CA into NoCal and SoCal for a total of 12 files. Important additional factors in evaluating risk include understanding fuel loading and fuel types, localized fire regimes, and identifying topographic features that enhance fire activity. The latter elements critically influence overall computed fire danger when coupled with the identified population centers.

The approach used for identifying these at-risk communities was a combination of initial heuristic assumptions, refined US 2000 census data, geographic information systems (GIS) data for identifying road networks and topography, and a previously established integer programming model. The programming model Critical Cluster Model (CCM) combines contiguous intersections—or "nodes", within a community (node set), with egress routes (exit links) in a pattern of arcs to extrapolate the maximum ratio of population-to-exits in a community. Constraints of the CCM were addressed through a region-growing algorithm. To acquire the initial data sets, a fire danger layer and a road network layer were applied; this resulted in the immediate removal of areas such as large cities or some desert areas where high fire danger/spread was not present, as well as all unpopulated areas. Through visual and computer generated location sorting, communities were identified that contained up to 100 contiguous intersections, had a minimum median fire hazard of 0.7 on a 0–1 scale, and had a minimum households-to-exit ration of 200 to one.

The computer generated results were grouped as communities with one, two, or three exits. These communities were then identified by state, number of nodes (intersections), and number of homes, fire hazard, and home-to-exit ratio. The highest home-to-exit ratios were then ranked within the three exit categories for identifying communities that exhibited the greatest concern for safety in an immediate egress situation. Cova *et al.* found that among all the western states, Southern California consistently exhibited a disproportionately high prevalence of communities of very limited egress with high fire hazard and topographical restraints. For example, they compare a community in WA that had a home-to-exit ratio of 320.9 to 1 (3 exits, 962.7 homes), with a community in SoCal that had a home-to-exit ratio of 1,566.8 to 1 (3 exits, 4,700.3 homes).

This study provides the first rigorous analysis covering a broad geographic area, which identifies and compares low-egress communities in fire-prone areas in the West. The authors however, strongly caution against using these results beyond the initial enumeration and ranking of fire-prone, low-egress communities in the western United States. They identified a number of significant limitations of their methods and results, largely based on outdated US census data (2000) and the potential of serious miscalculation on the basis of inaccurate GIS street network data for individual communities. This study can however be valued in terms of demonstrating cases of unchecked development in the WUI with little regard to public safety and emergency planning. It can serve as encouragement to local governments to more seriously consider this relatively new threat to public safety and property, by an environmental concern that is noticeably being exacerbated through climate change.

Community-based Model for Bioenergy Production Coupled to Forest Land Management for Wildfire Control using Combined Heat and Power

With wildfires becoming more frequent and severe in North America and around the world, forest management plans have come under review in an effort to mitigate higher fire suppression costs as well as human and climate induced fire regime changes. When implementing forest management plans, small communities located deep within the wildland urban interface (WUI) are often left out of the equation for reasons largely to do with economies of scale.

Yablecki et al. (2011) developed a comprehensive approach to treating fuels to minimize the threat of wildfires in remote areas while using the biomass generated from the forest treatment process for electrical generation, making the communities more sustainable and self-sufficient. Additionally this community-based model afforded long term lowered utility costs and greenhouse gas (GHG) emission reductions. The authors conclude that their proposition combines wildfire mitigation through forest treatment, power generation through use of biomass, and all other associated benefits, in a model that is entirely managed by the community.

Using previously published work and available information, Yablecki et al. established and presented a general understanding of the wildfire threats and range of energy (acquisition) needs, and coupled them with common fuels treatment processes and costs per hectare under forest management plans in the USA and Canada. An estimated 20,000 communities have been identified in the US as vulnerable to wildfires, many of the most severely threatened and previously impacted, lying within the Wildland Urban Interface (WUI)—the area where communities integrate into forested land. In these areas there is less access (escape routes), more dangerous fuel loading in close proximity to homes, and in more remote areas, very limited fire suppression resources. This study postulates that reactive fire management plans are no longer effective, and that in addition to other factors, proactive fuel treatment is preferred to heighten public safety, reduce the high cost of fire suppression activities, and to limit the devastating effects of home and business loss. In more remote communities, the authors propose an all encompassing model to accomplish the aforementioned goals, through community involvement and innovation in sustainable design, while addressing other community needs such as energy generation. In order to partially offset the cost of the forest treatment processes which are to occur every 15 years (in any given area), the use of onsite bioenergy generation is proposed under three models; operating scenarios are illustrated for two of them.

The first aspect of this model was an evaluation of fuel treatment costs in threatened communities. Costs were determined to vary from a low of $130 per hectare for prescribed fire alone, to nearly $3,000 per hectare with a combination of prescribed fire and mechanical treatment. Although the cost of mechanical treatment was significantly higher, so are the secondary use options, and hence the potential for additional revenue. One commonly associated issue with mechanical treatment is the cost of transporting removed biomass to be processed offsite—something unfeasible for very remote areas. Because the proposed model makes use of biomass onsite, these costs are eliminated. Biomass that was required to meet energy needs under three energy generating system types, were based on estimates of total annual energy use within a given community. The fuels treatment plan was adjusted accordingly to produce a sufficient amount of biomass for the bioenergy systems; the preferred 15–20 year cycles (estimated time before fuel loading becomes hazardous again) was taken into account and the threat of wildfires was greatly reduced under the new management plan.

The three proposed energy generating systems all fall under the category of combined heat and power (CHP) systems, and are best suited for small scale operations; they are therefore of the more appropriate technologies for these remote communities (most often removed from the power grid to begin with). They are the small-scale CHP steam Rankine system, the organic Rankine cycle (ORC), and the entropic cycle. The small-scale steam Rankine system produces high pressure steam for electricity generation through a direct-fired biomass conversion system that uses a boiler. This system however has the highest capital cost and requires specialized labor. The ORC system, of which there is a proven model commercially available in Europe, has a lower environmental impact and a higher operating efficiency with a 10% (electrical) energy conversion rate. However, it uses a variety of working fluids as alternatives to water, many of which are very volatile. The final approach evaluated, and found to be most suitable, was the entropic cycle. This system uses a process combination of the ORC system and small scale Rankine system to have an overall conversion efficiency of 68% with 12% representing the electrical conversion portion. The entropic cycle is the safest option, does not require specialized labor, and is a closed loop system so it does not require external cooling components and is therefore smaller in size.

Yablecki et al. chose a base case community of 100 residents expending an estimated 240kW (from three small diesel generators) for the modeling exercise; they used data from small communities in British Columbia as reference. They ran two scenarios with the selected three models. The first scenario utilized the CHP systems at 75–100% operating capacity year-round, while using some energy derived from diesel generators to offset a small portion of unmet energy needs in peak times (i.e. winter). The second scenario utilized only biomass; therefore the biomass required as well as the radius of fuel treatment needed, was greater. Between all three CHP energy systems, the entropic system proved to have the lowest capital investment, the highest return, and the lowest biomass input requirements. It therefore had the lowest need for labor intensive treatment processes and the associated costs as well.

To evaluate the GHG emission reductions as a consequence of this community based CHP bioenergy production and forest management model, the authors replaced gasoline fueled vehicles with electrical plug-in hybrid vehicles. This new fleet of vehicles could derive all their power from the CHP system(s) while only minimally expanding the community bioenergy production model, simultaneously reducing the communities GHG emissions and their dependency on imported fuels. Finally, Yablecki et al. formulated a loose revenue model largely based on overall long term savings while highlighting the revenue streams under the two scenarios. The payback periods under the Entropic and ORC systems were 18 and 24 years, respectively. Considered for example, were the fuels treatment costs per hectare (an average of $1389), and a fuel consumption of 4.8 L per 100km for the hybrid vehicles (PHEV60).

Though the authors cautioned against the variability possible when applying this model to different areas on different scales, they contend that it is a valuable comprehensive community-based solution that goes beyond just mitigating the often devastating effects of wildfires within the WUI in the US and Canada. Yablecki et al. suggest that this model revitalizes communities and addresses a host of issues from public safety, preventative forest fire mitigation practices in remote areas, and maintaining forest health, while reducing GHG emissions and dependence on imported fuels. Overall, this model, suited for small communities, is a sustainability and bioenergy model that uses mechanical forest treatment as its primary support and supply mechanism to provide a wide range of community benefits.

Conclusions

Increased drought episodes have become major drivers of increased fire activity as well as longer fire seasons. We saw that wildfire activity in Greece has visually been impacted by these annual and summer drought patterns. Furthermore, the current climate trajectory suggests that further similar trends will, affect the entire Mediterranean region. As China faces similar prospects, scientists hope that their studies can aide in shaping future fire management strategy and practice through knowledge of these future climate scenarios. They hope to accomplish that through improving activities such as prescribed burning and initial attack-phase fire suppression responses. The study that paid special attention to Alaska’s severe 2004 fire season is a response to aims of recognizing conditions for severe fire events in order to aide in predicting efforts needed by fire suppression forces in near-future situations. In other areas of the world that have less sophisticated or regimented fire management policies and response mechanisms, conducting these studies provide a context for developing fire prevention practices and policies while suggesting continued work in the subject area in order to translate study results into functioning fire prevention and suppression models for their country (such as Portugal). A major issue in the western United States is the unchecked development in the WUI with little regard to public safety and emergency planning. The study by Cova *et al.* can serve as a strong case and encouragement to local governments to more seriously consider this relatively new threat to public safety and property, by an environmental concern that is noticeably being exacerbated through climate change. Ultimately though, governments whether local or national will need to take multifaceted approaches towards addressing these issues if they are going to be successful in guaranteeing public safely, economic stability and environmental protection. Although the small community model for bioenergy generation and forest management practices to provide a wide range of community benefits is not suited for all circumstances, it is proposed in the right spirit of ingenious problem solving and solution building—approaches policymakers should consider seriously.

References Cited

Cova, Thomas J., Theobald, David M., Norman III, John B., Siebeneck, Laura K., 2011. Mapping Wildfire Evacuation Vulnerability in the Western US: the Limits of Infrastructure. GeoJournal, Springer Science+Business Media B.V. 2011.

Dimitrakopoulos, Alexandros P., Vlahou, M., Anagnostopoulou, Ch. G., Mitsopoulos, I. D., 2011. Impact of drought on wildland fires in Greece: implications of climatic change? Springer Science+Business Media B.V. 2011. Climate Change.

IPCC, 2007: Summary for Policymakers. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning,Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Justino, Flavio, S. de Mélo, A., Setzer, A., Sismanoglu, R., Sediyama, G. C., Ribeiro, G. A., Machado, J. P., Sterl A. , 2010. Greenhouse gas induced changes in the fire risk in Brazil in ECHAM5/MPI-OM coupled climate model. Climatic Change (2011) 106, 285–302.

Mack, Michelle C., Bret-Harte, M. Syndonia, Hollingsworth, Teresa N., Jandt, Randi R., Schuur, Edward A. G., Shaver, Gaius R., Verbyla, David L., 2011. Carbon Loss from an Unprecedented Arctic Tundra Wildfire. *Nature* 475, 489–492.

Marques, S., Borges, J. G. J., Garcia-Gonzalo, Moreira, F., Carreiras, J. M. B., Oliveira, M. M., Cantarinha, A., Botequim, B., Pereira, J. M. C., 2011. Characterization of wildfires in Portugal. European Journal of Forest Research 130, 775–784.

Metz, Margaret R., Frangioso, Kerri M., Meentemeyer, Ross K., Rizzo, David M., 2011. Interacting disturbances: wildfire severity affected by stage of forest disease invasion. Ecological Applications 21, 313–320.

North, Malcolm P., Hurteau, Matthew D., 2011. High-severity wildfire effects on carbon stocks and emissions in fuels treated and untreated forest. Forest Ecology and Management 261, 1115–1120.

O'Donnell, Alison J., Boer, Matthias M., McCaw, W. Lachlan, and Grierson, Pauline F., 2011. Vegetation and landscape connectivity control wildfire intervals in unmanaged semi-arid shrublands and woodlandsin Australia. Journal of Biogeography 38, 112-124.

Wathen, Stephen F., 2011. 1,800 Years of abrupt climate change, severe fire, and accelerated erosion, Sierra Nevada, California, USA. Climatic Change 108, 333–356

Wendler, G., Conner, J., Moore, B., Shulski, M., Stuefer, M., 2010. Climatology of Alaskan wildfires with special emphasis on the extreme year of 2004. Theoretical and *Applied* Climatology (2011), 104:459–472

Xiao-rui, T., Li-fu, S., Feng-jun, Z., Ming-yu, W., McRae, Douglas J., 2011. Future impacts of climate change on forest fire danger in northeastern Chin. Journal of Forestry Research 22, 437–446.

Yablecki, Jessica, Bibeau, Eric L., Smith, Doug W., 2011. Community-based model for bioenergy production coupled to forest land management for wildfire control using combined heat and power. Biomass and Bioenergy 35, 2561–2569.