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IMPACT OF GLOBAL WARMING ON THE CARBON SEQUESTRATION POTENTIAL AND STAND DYNAMICS OF CHIR PINE FORESTS

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ABSTRACT

A process-based in silico simulation study of the impact of carbon dioxide fertilisation and temperature escalation on the carbon sequestration potential and stand dynamics of Chir Pine forests of Almora district of Uttarakhand, India was undertaken utilising allometric equations and physiological process equations to discern carbon flows, assimilation and allocation as affected by site, environment, soil water, stocking and mortality inputs under varying representative concentration pathways (RCPs) of the IPCC. The simulation predicted that carbon dioxide fertilisation and temperature escalation shall have opposing ramifications on stand volume, mean annual increment, leaf area index, gross primary productivity and carbon sequestration potential of the Chir Pine stands. Which of these two factors shall dominate was found to be contingent upon their relative strengths, the age of the stand, and other parameters. The carbon sequestration potential of the Chir Pine forests under this study got augmented with successive RCPs; thus they were found to be suitable candidates for substantiating climate change mitigation efforts.

Key words: Forest stand, Global warming, Climate change mitigation, Modelling, Simulation, Species selection.

Introduction

Afforestation has been a kingpin in our endeavours to mitigate global climate change and global warming (Bonan, 2008; Canadell and Raupach, 2008; Trabucco *et al*., 2008; Zomer *et al*., 2008; Read *et al*., 2009). It is known that through the process of photosynthesis, trees convert sunlight into bioenergy, sequestering concomitantly in this process carbon dioxide of the atmosphere into plant biomass. Carbon dioxide being a key factor driving global warming and climate change, sequestration of this compound is believed to help mitigate climate change (Grimston *et al.*, 2001; Bachu and Adams, 2003; Lackner, 2003; Metz *et al.,* 2005; Hansen *et al*., 2008).

However, in the strategy of utilising afforestation for climate change mitigation, several questions still remain, including the selection of the best species for a particular site, with regards to the prevailing site and climatic conditions (Guariguata *et al*., 2008; Gera *et al*., 2016; Gera *et al*., 2016). Further, the impact of global warming on the stand dynamics of the chosen species at the particular site also needs to be considered for optimal decision making (Eamus and Jarvis, 1989; Dale *et al*., 2001; Millar *et al*., 2007; Allen *et al.,* 2010; Lindner *et al.,* 2010). This is because for afforestation to work in mitigating climate change, the need is for mechanisms that shall assert a negative feedback loop on global warming. That is to say, as global warming intensifies, we'll require the stands to sequester more and more carbon, and thus counter global warming more effectively. On the other hand, if such species that are capable of sequestering less carbon in the escalated global warming scenarios, we could have overall sub-optimal levels of carbon sequestration globally, thus defeating our purpose of climate change mitigation. Hence, we need to analyse not only whether the selected species could thrive at the chosen site, but also the impacts global warming would have on the forest stand dynamics of the chosen species at the chosen sites to enable us to determine fruitfully the suitable species for climate change mitigation for all sites.

The impact of global warming on the forest stands can be studied under two mechanisms. Carbon dioxide, being a reactant in the process of photosynthesis, is believed to 'fertilise' forest stands (Friedlingstein *et al.,* 1995; Farquhar, 1997; Donohue *et al.,* 2013). Thus, as the concentration of carbon dioxide in the air increases, the stands are able to do more photosynthesis, and so sequester more carbon, thereby contributing more fruitfully towards our climate change mitigation efforts by providing a negative feedback. The impact of warming, on the other hand, may be beneficial or detrimental on a particular forest stand (Dougherty and Hennessey, 1987; Adams and Kolb, 2005; Matala *et al*., 2005; Williams *et al*., 2013). As a result, the net impact of global warming on a particular forest stand may range from strongly positive,

CO_2 fertilization and temperature escalation have opposite impact on the stand volume, mean annual increment, leaf area index, gross primary producitivity and carbon sequestration potential.

through neutral, to strongly negative. In this paper, we describe the application of computer simulation to discern the net impact of global warming on Chir Pine forest stands. We also study how the two factors, carbon dioxide fertilisation and temperature escalation impact the forest stands. We believe that the results of this study shall prove consequential for furthering our climate change mitigation efforts through the utilisation of large-scale afforestation programs.

Material and Methods

Gathering of climate data for Almora district of Uttarakhand

The raw climatic data for the past 100 years for the Almora district of Uttarakhand was downloaded from the India Water Portal (http://www.indiawaterportal.org). The data was plotted to reveal the natural variations existent in the climatic parameters' values for every month. These variations were smoothened by taking averages over the long period.

Calibration of the simulation model

The 3PG model (Physiological Principles Predicting Growth) (Kirschbaum *et al.,* 2001; Almeida *et al.,* 2004) employed in this study was parametrised and calibrated before use by utilising the stand volume, tree density and stand basal area data from the yield table published by FRI Dehradun, and using the values of leaf area index as available from published literature (Shi and Cao, 1997; Richardson, 2000). Parametric values such as biomass partitioning and turnover allometric relationships, litter fall values, etc. were also taken from published literature on *Pinus roxburghii* (Mason, 2004), with modifications for Indian conditions. Calibration of the model was done till the output from the simulation closely matched the values available from the yield table and the published literature.

Simulation of the Pine stand at Almora under different global warming scenarios

The 3PG model is available in the form of a spreadsheet application in which various stands can be simulated through allometric equations. The model was used to study the impacts of global warming on a number of stand parameters (stand volume, mean annual increment, leaf area index, gross primary productivity and carbon sequestration). To differentiate the impacts of carbon dioxide augmentation and temperature escalation, the studies were divided into three components. First, the carbon dioxide concentrations were modified keeping the other climatic parameters constant at the ambient conditions. This depicted the impacts of carbon dioxide augmentation alone under the prevailing climatic conditions. Similarly, in another set of studies, the impact of temperature escalation alone was mimicked by modulating radiative forcing under constant ambient concentrations of carbon dioxide (fixed at 360 ppm, the contemporary concentration). Finally, both carbon dioxide concentrations and radiative forcing were permitted to portray their roles concomitantly, to simulate their joint impacts under future scenarios.

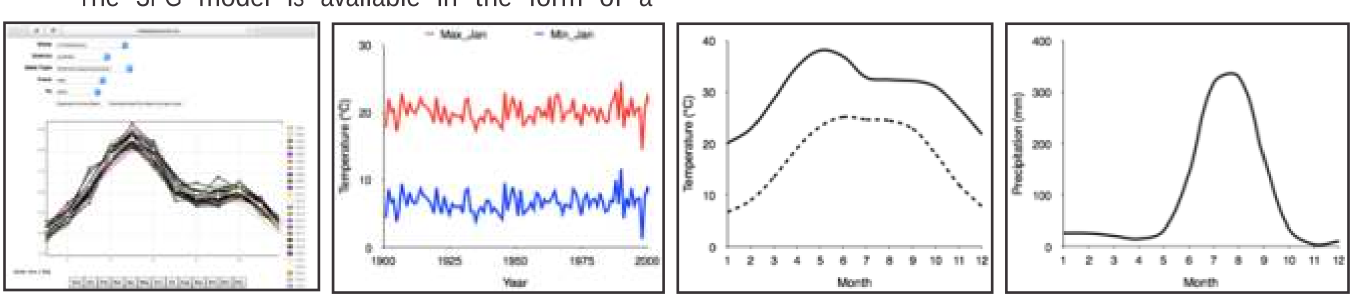
Results and Discussion

The climate data for Almora district of Uttarakhand

The 100-year raw climatic data for Almora district of Uttarakhand was downloaded from http://www.indiawaterportal.org (Fig. 1a). The climate data so obtained displays the naturally occurring variations in the temperature and precipitation values for every month over the century (Fig. 1b). To smoothen these variations, averages were taken over the period to obtain the average maximum and minimum temperatures for each month at Almora (Fig. 1c), and the average precipitation for each month at Almora (Fig. 1d).

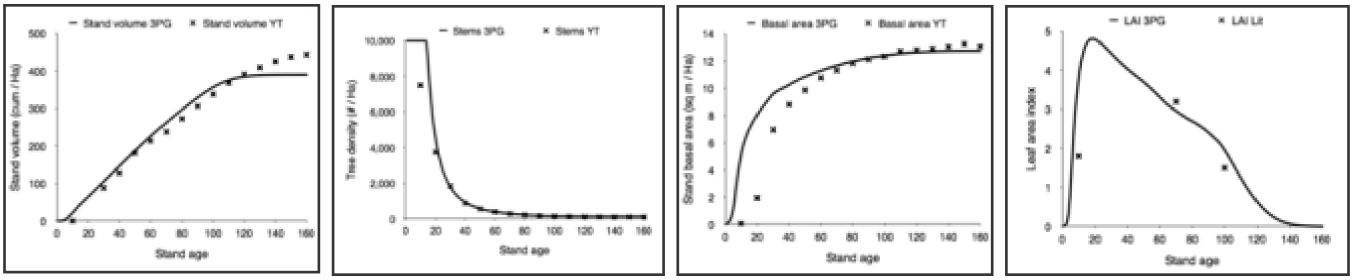
Calibration of the 3PG model for the pine stand at Almora

The model was parametrised and calibrated before use utilising the stand volume, tree density and stand basal area data from the yield table published by FRI, and using the values of leaf area index available from published



(a) (b) (c) (d)

Fig. 1: Gathering of climatic data for Almora district of Uttarakhand. (a) The 100-year raw data was downloaded from http://www.indiawaterportal.org (b) The climate data over the century displays natural variations in the values of the climatic parameters for every month. (c) To smooth these variations, averages were taken over the period. The figure depicts the average maximum and minimum temperatures for each month at Almora. (d) The average precipitation for each month at Almora.



(a) (b) (c) (d)

Fig. 2: The results obtained after the calibration process. The variation of stand volume (a), tree density (b), stand basal area (c) and leaf area index (d) with the age of the stand are depicted. The smooth lines show the results obtained from the simulation model, while the crosses portray the values from the yield table (a-c) or from published literature (d).

literature. After the process of calibration, the model's output of theage-dependent variation in the stand volume (Fig. 2a), tree density (Fig. 2b), stand basal area (Fig. 2c) and the leaf area index (Fig. 2d) closely matched the published values. The smooth lines in Fig. 2 show the results obtained from the simulation model, while the crosses portray the values from the yield table (Fig. 2 a-c) or from published literature (Fig. 2d). Since the model agreeably simulated the contemporary conditions, we considered it capable now of being utilised for the simulation of future conditions of climate change.

Simulation of stand volume for different global warming scenarios

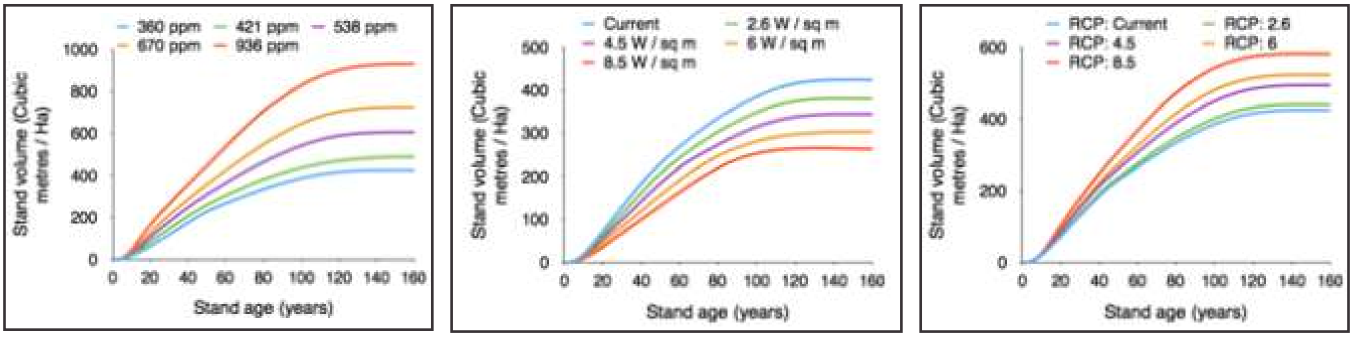
The result of the simulation of stand volume for different global warming scenarios is depicted in fig. 3. Fig. 3a represents the impact of carbon dioxide augmentation only under ambient climatic conditions. 360 ppm is the contemporary carbon dioxide concentration of air. 421 ppm is the concentration of carbon dioxide that would cause a radiative forcing of 2.6 Watts per square metre, referred to as RCP 2.6. RCP stands for representative concentration pathway trajectories as defined by the IPCC in their fifth assessment report 2014 (IPCC 2014). 538 ppm, 670 ppm and 936 ppm, similarly, are the carbon dioxide concentrations corresponding to RCP 4.5, RCP 6 and RCP 8.5 situations. We can observe that the curves have the familiar sigmoidal shape that we get by plotting stand volume per hectare versus the age of the stand (Laar, 1991; Williams *et al*., 2014). We also observe that when carbon dioxide concentrations increase under current temperatures, the curves shift upwards, indicating the fertilising impact of carbon dioxide over stand volume. This phenomenon is well reported in the published literature (Friedlingstein *et al.,* 1995; Farquhar, 1997; Donohue *et al*., 2013).

The impact of radiative forcing only on the forest stand (keeping the carbon dioxide concentration fixed at the current conditions of 360 ppm) is depicted in fig. 3b. The simulated radiative forcing values of 2.6 W / m^2, 4.5 W / m^2, 6 W / m^2 and 8.5 W / m^2, correspond to RCP 2.6, 4.5, 6 and 8.5 conditions, respectively. It was observed that the radiative forcing, by increasing ambient temperatures, reduces the stand volume per hectare, and the curves shift downwards. Intuitively, it can be explained by considering the fact that pines are species of low temperatures, so higher temperatures could be pushing them outside their norm of reaction. This phenomenon is also well reported in the published literature (Nedlo *et al*., 2009).

The joint impact of increasing temperatures and carbon dioxide concentrationsunder current conditions and simulated RCP 2.6, 4.5, 6 and 8.5 conditions is depicted in fig. 3c. In this particular case, the carbon dioxide fertilisation effect dominates. However, we also observe by looking at the y-axis scales of figures 3a and 3c that the magnitude of the fertilisation effect has diminished considerably, from around 2.5 times in the case of CO_2 fertilisation under ambient climatic conditions (In fig. 3a, the max. stand volume increases from 400 m^3 / ha to 1000 m^3 / ha when CO_2 concentration increases from 360 ppm to 936 ppm) to only around 1.5 times in the case of the joint impact situation (In fig. 3b, the max. stand volume increases from 400 m^3 / ha to 600 m^3 / ha when CO_2 concentration increases from 360 ppm to 936 ppm and radiative forcing is 8.5 W / m^2). The simulation also suggests that till RCP 2.6 conditions, the impacts on stand volume shall be negligible (Fig. 3c).

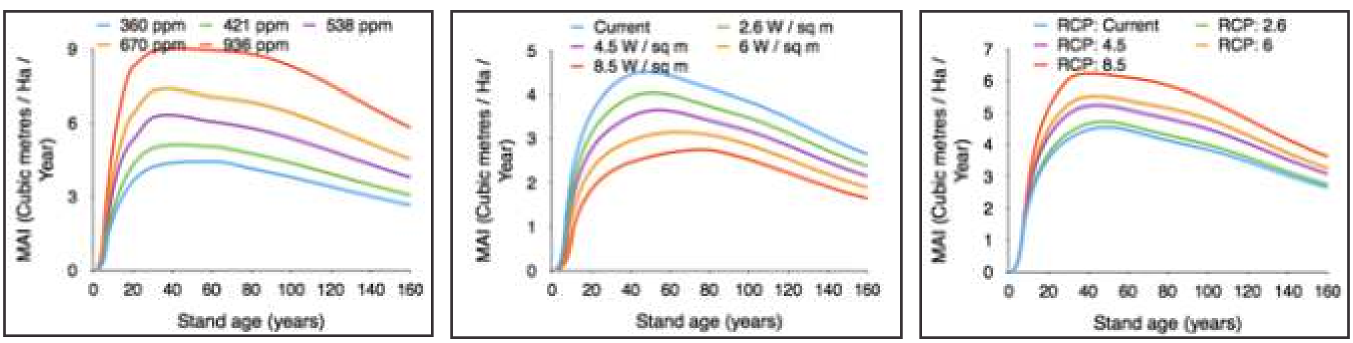
Simulation of mean annual increment for different global warming scenarios

The impact of global warming on the mean annual increment per hectare is depicted in fig. 4, with fig. 4a representing the impact of carbon dioxide augmentation only under ambient climatic conditions, Fig. 4b representing the impact of temperature escalation only under current carbon dioxide concentrations, and fig. 4c representing the combined impact of carbon dioxide augmentation and temperature escalation under current conditions and simulated future RCP conditions.



(a) (b) (c)

Fig. 3: Simulation of stand volume under different global warming scenarios. (a) represents the impact of carbon dioxide augmentation only under ambient climatic conditions. 360 ppm is the current carbon dioxide concentration of the atmosphere, while 421 ppm, 538 ppm, 670 ppm and 936 ppm represent the carbon dioxide concentrations under RCP 2.6, 4.5, 6 and 8.5 conditions, respectively. (b) represents the impact of temperature escalation only under current carbon dioxide concentrations. These are calculated using the current radiative forcing, and simulated radiative forcing values of 2.6 W / m^2, 4.5 W / sq m, 6 W / m^2 and 8.5 W / m^2, corresponding to RCP 2.6, 4.5, 6 and 8.5 conditions, respectively. (c) represents the combined impact of carbon dioxide augmentation and temperature escalation under current conditions and simulated RCP 2.6, 4.5, 6 and 8.5 conditions.



(a) (b) (c)

Fig. 4: Simulation of mean annual increment under different global warming scenarios. (a) represents the impact of carbon dioxide augmentation only under ambient climatic conditions. 360 ppm is the current carbon dioxide concentration of the atmosphere, while 421 ppm, 538 ppm, 670 ppm and 936 ppm represent the carbon dioxide concentrations under RCP 2.6, 4.5, 6 and 8.5 conditions, respectively. (b) represents the impact of temperature escalation only under current carbon dioxide concentrations. These are calculated using the current radiative forcing, and simulated radiative forcing values of 2.6 W / m^2, 4.5 W / m^2, 6 W / m^2 and 8.5 W / m^2, corresponding to RCP 2.6, 4.5, 6 and 8.5 conditions, respectively. (c) represents the combined impact of carbon dioxide augmentation and temperature escalation under current conditions and simulated RCP 2.6, 4.5, 6 and 8.5 conditions.

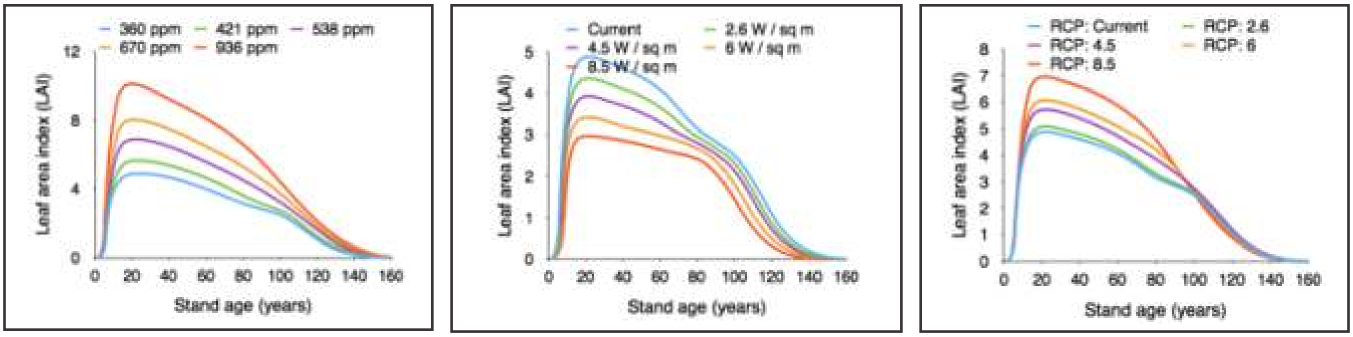
As in the previous section, here too we observe that while the curves have familiar shapes as reported in the literature (Laar, 1991; Roberge *et al*., 2016), and carbon dioxide fertilisation (Fig. 4a) and temperature enhancements (Fig. 4b) have opposing impacts on MAI, the overall impact is minuscule till the RCP 2.6 situation (Fig. 4c). Similar results for the impacts of carbon dioxide fertilisation and temperature enhancement on MAI have also been reported previously in the published literature (Loustau *et al.*, 2005).

Simulation of leaf area index for different global warming scenarios

Fig. 5 depicts the simulation of leaf area index of the stand for different global warming scenarios. Similar to the observations in the previous sections, it was observed that carbon dioxide fertilisation (Fig. 5a) and temperature enhancements (Fig. 5b) have opposing impacts on the leaf area index. However, in the joint impact situation (Fig. 5c), a new phenomenon was observed which was not seen previously: The curves intersect at around 100 years of stand age. Thus, in the balance of forces between carbon dioxide fertilisation and temperature enhancements, age can also play a vital role. This can be explained considering the fact that the younger crops are more tolerant to adverse conditions and better at exploiting favourable conditions than the older crops (Gower *et al*., 1996; Linder, 2000).

Simulation of gross primary productivity for different global warming scenarios

A similar picture appears with gross primary productivity. It was observe that carbon dioxide fertilisation (Fig. 6a) and temperature enhancements (Fig. 6b) have opposing impacts on the gross primary productivity under different global warming scenarios. An age-dependent



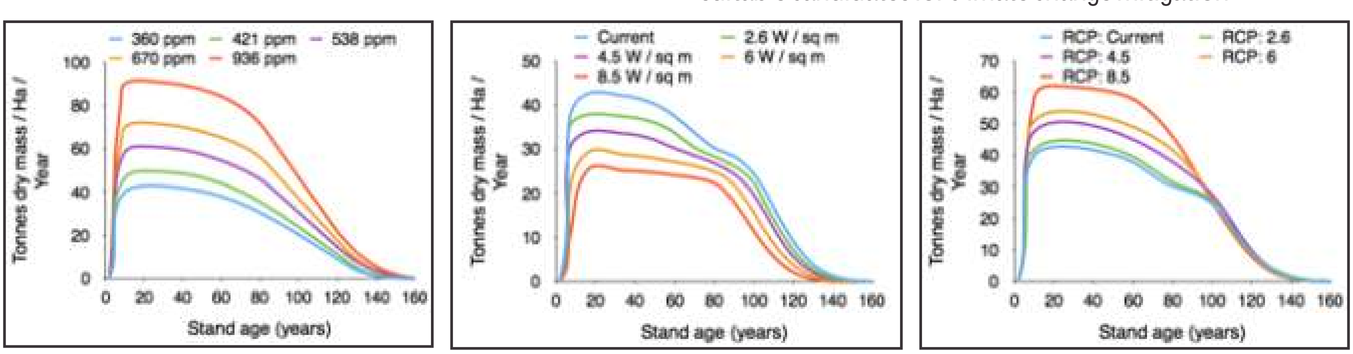
(a) (b) (c)

Fig. 5. Simulation of leaf area index under different global warming scenarios. (a) represents the impact of carbon dioxide augmentation only under ambient climatic conditions. 360 ppm is the current carbon dioxide concentration of the atmosphere, while 421 ppm, 538 ppm, 670 ppm and 936 ppm represent the carbon dioxide concentrations under RCP 2.6, 4.5, 6 and 8.5 conditions, respectively. (b) represents the impact of temperature escalation only under current carbon dioxide concentrations. These are calculated using the current radiative forcing, and simulated radiative forcing values of 2.6 W / sq m, 4.5 W / m^2, 6 W / m^2 and 8.5 W / m^2, corresponding to RCP 2.6, 4.5, 6 and 8.5 conditions, respectively. (c) represents the combined impact of carbon dioxide augmentation and temperature escalation under current conditions and simulated RCP 2.6, 4.5, 6 and 8.5 conditions.

response towards the opposing impacts of carbon dioxide fertilisation and temperature enhancements in the joint impact situation (Fig. 6c) was also observed.

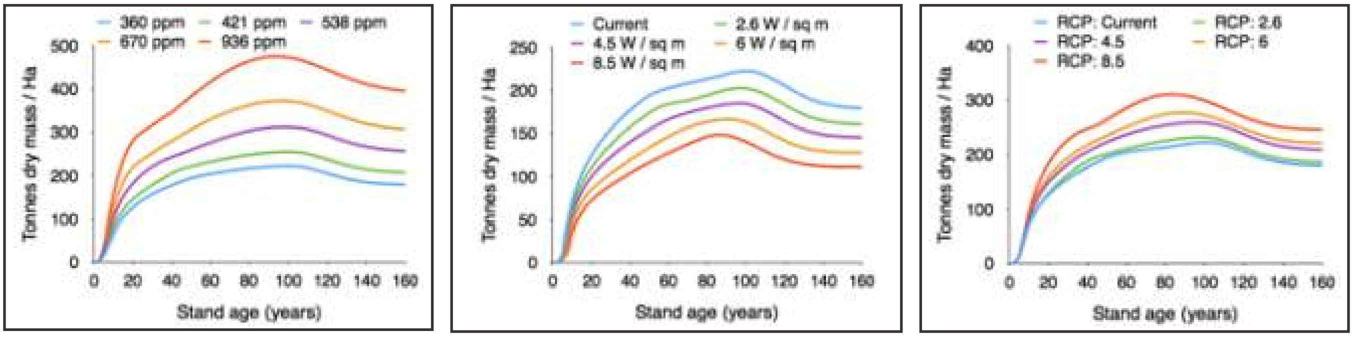
Simulation of carbon sequestration for different global warming scenarios

The efficiency of carbon sequestration, as observed by the accumulation of dry matter mass per hectare of the stand also represents the opposing impacts of carbon dioxide fertilisation (Fig. 7a) and temperature enhancements (Fig. 7b). The fact that increased temperatures result in decreased amounts of net carbon sequestration, especially due to aggravated mortality rates is well reported in the literature (Allen, 2009; Van Mantgem *et al*., 2009; Williams *et al*., 2010; Das *et al*., 2013; McDowell and Allen, 2015). Here it was also observed that the amount of accumulated dry mass reached a peak and then decreased afterwards as the stands age, mostly since the model also accounts for the mortality occurring in older stands. This could indicate the point where the stands become net emitters of carbon, and we need to harvest the stands at or before this point for climate change mitigation purposes. The peak shifts under the changing RCP conditions (Fig. 7c), indicating that the age for harvest changes with the changing ambient conditions, and that is something we need to consider in our management operations when we wish to target climate change mitigation through carbon sequestration by forests. It can be observed from fig. 7c that the sequestration potential of the Chir Pine forests at Almora increases with successive representative concentration pathways. As global warming increases, the stands sequester more carbon, providing a negative feedback to global warming. Thus they appear suitable candidates for climate change mitigation.



(a) (b) (c)

Fig. 6: Simulation of gross primary productivity under different global warming scenarios. (a) represents the impact of carbon dioxide augmentation only under ambient climatic conditions. 360 ppm is the current carbon dioxide concentration of the atmosphere, while 421 ppm, 538 ppm, 670 ppm and 936 ppm represent the carbon dioxide concentrations under RCP 2.6, 4.5, 6 and 8.5 conditions, respectively. (b) represents the impact of temperature escalation only under current carbon dioxide concentrations. These are calculated using the current radiative forcing, and simulated radiative forcing values of 2.6 W / m^2, 4.5 W / m^2, 6 W / m^2 and 8.5 W / m^2, corresponding to RCP 2.6, 4.5, 6 and 8.5 conditions, respectively. (c) represents the combined impact of carbon dioxide augmentation and temperature escalation under current conditions and simulated RCP 2.6, 4.5, 6 and 8.5 conditions.



(a) (b) (c)

Fig. 7: Simulation of carbon sequestration under different global warming scenarios. (a) represents the impact of carbon dioxide augmentation only under ambient climatic conditions. 360 ppm is the current carbon dioxide concentration of the atmosphere, while 421 ppm, 538 ppm, 670 ppm and 936 ppm represent the carbon dioxide concentrations under RCP 2.6, 4.5, 6 and 8.5 conditions, respectively. (b) represents the impact of temperature escalation only under current carbon dioxide concentrations. These are calculated using the current radiative forcing, and simulated radiative forcing values of 2.6 W / m^2, 4.5 W / m^2, 6 W / m^2 and 8.5 W / m^2, corresponding to RCP 2.6, 4.5, 6 and 8.5 conditions, respectively. (c) represents the combined impact of carbon dioxide augmentation and temperature escalation under current conditions and simulated RCP 2.6, 4.5, 6 and 8.5 conditions.

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चीड़ पाइन वनों की स्टैण्ड गतिकी और कार्बन पृथक्करण क्षमता पर विश्व तापन का प्रभाव

अंकुर अवधिया

सारांश

आई पी सी सी के अलग–अलग प्रतिनिधि सान्द्रता मार्गों के अन्तर्गत कार्बन प्रवाहों, संचयन एवं आबंटन, जैसा स्थल द्वारा प्रभावित किया गया, पर्यावरण, मृदा जल, स्टाकिंग एवं मर्त्यता निवेशों को जानने के लिए एलोमेट्रिक समीकरणों और शारीरिकीय प्रक्रिया समीकरणों का उपयोग करके उत्तराखंड, भारत के अल्मोड़ा जिले के चीड़ पाइन वनों की स्टैण्ड गतिकी और कार्बन पृथक्करण क्षमता पर कार्बन डाइऑक्साइड उर्वरण एवं तापमान वृद्धि के प्रभाव के सिलिको अनुरूपण अध्ययन पर आधारित एक प्रक्रिया की गई। अनुरूपण ने भविष्य कथन किया कि कार्बन डाइऑक्साइड उर्वरण और तापमान वृद्धि का चीड़ पाइन स्टैंडों के स्टैण्ड आयतन, औसत सालाना वृद्धि, पत्ती क्षेत्र तालिका, कुल प्राथमिक उत्पादकता और कार्बन पृथक्करण क्षमता पर विरोधी प्रशाखन होगा, इनमें से दो कारक प्रभुत्व करेंगे, जिन्हें उनके सापेक्ष सामर्थ्यों, स्टैण्ड की आयु तथा अन्य पैरामीटरों के ऊपर संभाव्य पाया गया। इस अध्ययन के तहत चीड़ पाइन वनों की कार्बन पृथक्करण क्षमता को आनुक्रमिक प्रतिनिधि सान्द्रता मार्गों (आर.सी.पी.) के साथ संवर्धित किया गया। इस प्रकार इन्हें जलवायु परिवर्तन न्यूनीकरण प्रयासों को सिद्ध करने के लिए उपयुक्त अभ्यर्थी पाया गया है।

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