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ORIGINAL PAPER

# Evaluating the vegetation destruction and recovery of Wenchuan earthquake using MODIS data

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**Abstract** The Ms 8.0 Wenchuan earthquake in 2008 has led to huge damage to land surface vegetation in northwest Sichuan, one of the typical ecological fragile regions in China. In this paper, the vegetation degradation by the earthquake and its recovery after the disaster are evaluated from analysis of MODIS Gross Primary Productivity (GPP) time series products and other ancillary GIS data. The results suggest that local vegetation GPP after the earthquake in the heavy afflicted area has decreased by 22%. The local vegetation productivity in the heavy afflicted area had recovered to 84 and 87% after 1 and 2 months later. Since August 2008, the vegetation productivity has increased to a nearly normal level.

**Keywords** Wenchuan earthquake · Vegetation degradation · Vegetation recovery · MODIS

## 1 Introduction

Natural disturbance is one of the most important factors driving the ecosystem development (Attiwill 1994). Earthquake, as a typical catastrophic disturbance event, is important in creating patterns of ecosystems composition and structure (Attiwill 1994). For example, Chilean earthquake of March 3, 1985 caused extensive mortality of intertidal organisms at the Estación Costera de Investigaciones Marinas, Las Cruces (Castilla et al. 1988). The 1999 Izmit earthquake resulted in costal environment contamination in Izmit Bay (Okay et al. 2001). The tsunamis from the great Sumatran earthquakes severely damaged the structure and function of the local coastal ecosystems, which affected the region for many years (Cochard et al. 2008).

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At 2:28 p.m. local time on May 12th, 2008, a magnitude 8.0 earthquake broke out in Sichuan province, China. All China except a few provinces were shaken, the county seats with the range of 50 km and cities with the range of 200 km from the epicenter were influenced seriously by the disaster. More than 69,000 people are dead and about 18,000 are missing (Chinese Seismic Information Site, http://www.csi.ac.cn/sichuan/index080512.htm). The Wenchuan earthquake is located at the Minshan-Hengduan Mountains. This region is a national key ecological function zone of biodiversity conservation, which houses more than 4,000 species of plants and animals, including the primary reserves for China's endangered icon, the giant panda. The mainshock and aftershocks destroyed terrestrial vegetation. And, 13 days continuous rainfall after the disaster caused significant concomitant secondary geological hazards, such as debris flows and landslides, which made vegetation mortality increased (Ren et al. 2009). The disaster area is also the water conservation region of Chendu plain. Earthquake-induced vegetation destruction has probably threatened the water supply of Chendu plain and the habitat of local wildlife. Therefore, it is valuable to monitor the local vegetation change after the earthquake.

Vegetation degradation means a reduction of the productive potential of the land (Reynolds et al. 2007). Gross Primary Productivity (GPP), which represents the photosynthetic capacity of vegetation, can be used to characterize vegetation productive capability and be estimated from remote sensing. Here, we use the GPP as vegetation productive capability index to evaluate the vegetation destruction in the disaster and its restoration after that.

## 2 Methods and materials

The study area covers the main afflicted 23 counties in the northwest Sichuan, China (Fig. 1). MODIS Gross Primary Productivity products (MOD17A2) and Surface-Reflectance products (MOD09A1) from January 1, 2004 to November 16, 2009 are used to detect local vegetation responses to the Wenchuan earthquake.

MODIS Surface-Reflectance Product (MOD09) is the surface spectral reflectance for seven bands from satellite observations as if they were measured at ground level. The atmospheric correction is performed by the dark-object method though 6S radiation transfer model (Vermote et al. 2002). The 8-days composite 500 m red, green and blue band land surface reflectances (MOD09A1) are used to find the clear-sky images. MODIS Gross Primary Vegetation Productivity product (MOD17A) provides global cumulative composite of GPP, net photosynthesis at 1-km spatial resolution. The GPP algorithm bases on the radiation use efficiency concept, with the input of MODIS landcover, FPAR/LAI and global MAO surface meteorology data (Zhao et al. 2005). The 8-days composite Gross Primary Vegetation Productivity products (MOD17A2) during 2004–2009 are used to analyze the vegetation productivity capability in the study area. After many comparisons of the MODIS products and ground-based measurements which are performed covering a wide range of biome types, Turner et al. (2006) suggested that the MODIS GPP products are responsive to general trends in the magnitude of GPP associated with local climate and land use without overall bias. In this paper, the MODIS GPP products could capture the changes of local vegetation. MODIS QA data are used to exclude cloud and non-vegetated pixels to ensure the confidence of analysis. All MODIS data used are downloaded from https://wist.echo.nasa.gov/api/.

Firstly, several tiles of MODIS land surface reflectance and GPP data in the study area are transformed to Albers equal area projection and composed to one map. The urban,

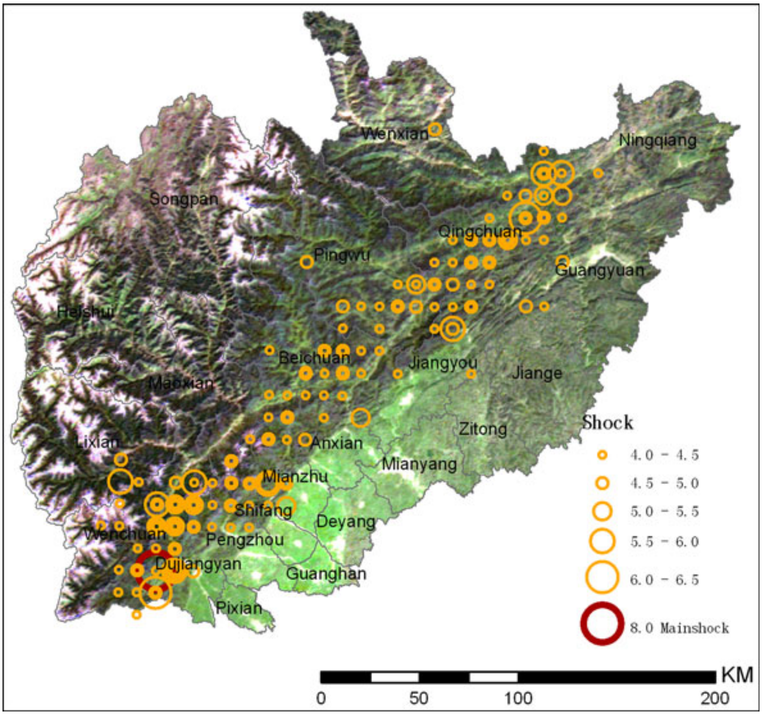
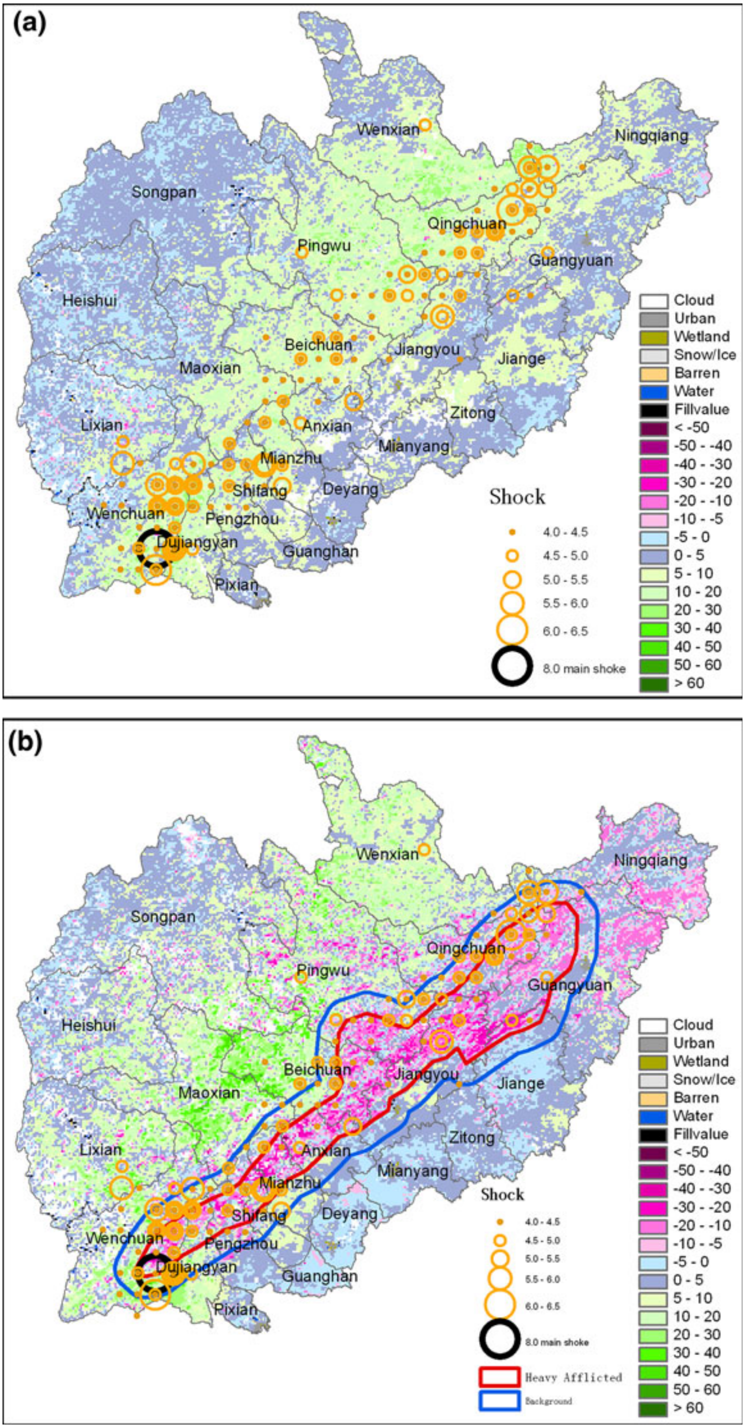



**Fig. 1** Map of Wenchuan earthquake and aftershocks until 2008.7.25 ($M \geq 4$)

wetland, water, barren, snow/ice, cloud and fillvalue pixels are then labeled using GPP fillvalue and QA data. The remaining pixels are labeled as vegetation.

The composed color images from MODIS surface reflectance data are used to select clear-sky GPP products after earthquake occurred. After the earthquake, continuous cloud cover in the disaster area was unfavorable to remote sensing. According to RGB maps of MODIS band 1, 4, 3 surface reflectance, clear sky data of study area was obtained during June 1st, 2008 to June 8th, 2008. So MODIS GPP data in June 1, 2008 to June 8, 2008 are selected as representative of local vegetation condition after the earthquake. The mean GPP map which is calculated by averaging the clear-sky GPP value in June 1–8 during 2004 to 2007 is used as reference data of local vegetation's normal condition. The difference map is conducted by using clear-sky satellite data after the earthquake (June 1–8, 2008) and the reference mean GPP map from 2004 to 2007 in the same composite period. This GPP difference image (Fig. 2b) derived from the two GPP maps mentioned above is used to identify areas where there had been a significant change in vegetation canopy reflectance. A high negative value indicates a trend of reduced canopy cover and/or vegetation vigor. While a positive value conversely indicates image pixels where there had been an increase in canopy cover or vegetation vigor. Similar studies are also conducted using clear-sky GPP data acquired just before the earthquake (May 1–8, 2008) to represent the vegetation condition before the disaster and evaluate the effect of climate fluctuation (Fig. 2a).

In addition to vegetation damage, the vegetation restoration is also evaluated. The concentrated distribution area of negative value in the GPP difference map after the


(a)
Wenxian
Ningqiang
Songpan
Qingchuan
Pingwu
Guangyuan
Heishui
Beichuan
Jiangyou
Jiange
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Zitong
Lixian
Anxian
Mianyang
Mianzhu
Shifang
Deyang
Wenchuan
Pengzhou
Dujiangyan
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Barren
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-30 - -20
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-5 - 0
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10 - 20
20 - 30
30 - 40
40 - 50
50 - 60
> 60
(b)
Wenxian
Ningqiang
Songpan
Qingchuan
Pingwu
Guangyuan
Heishui
Beichuan
Jiangyou
Jiange
Maoxian
Zitong
Lixian
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Mianzhu
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Wenchuan
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0 - 5
5 - 10
10 - 20
20 - 30
30 - 40
40 - 50
50 - 60
> 60

◀ **Fig. 2** **a** GPP difference map before earthquake (unit: g C/m$^2$); **b** GPP difference map after earthquake (unit: g C/m$^2$). The concentrated distribution area of negative value in Fig. 2b is labeled as heavy afflicted area (*red line*), and the buffer area with the distance of about 11,000 m around the heavy afflicted area is labeled as background area (*blue line*)

earthquake is labeled as heavy afflicted area. Monthly mean GPP maps from January 2008 to November 2009 are calculated by averaging the clear-sky values in each month. The reference monthly mean GPP map are calculated by averaging the clear-sky values in the corresponding month from 2004 to 2007, which is assumed as the representative of local vegetation productivity capability without disturbance. The two GPP maps mentioned above are then composed to the heavy afflicted area, and the vegetation change state is evaluated by using vegetation productive capability index (VPC):

$$\mathrm{VPC} = \frac{\mathrm{GPP}}{\mathrm{GPP_{Ref}}} \times 100\%.$$

GPP in the formula is the average of monthly mean GPP of vegetated pixels in the heavy afflicted area, while $\mathrm{GPP_{Ref}}$ is the average of reference monthly mean GPP of vegetated pixels in the heavy afflicted area. The GPP values of labeled urban, wetland, water, barren, snow/ice pixels are set to zero, and the GPP of cloud and fillvalue pixels use the average of the vegetated pixels. The VPC value higher than 100% means the vegetation growth is more vigorous than the normal, while the VPC lower than 100% means the vegetation growth is worse than the normal. When the value is close to 100%, the vegetation grows normally as before. Monthly VPC values are calculated from January 2008 to November 2009.

Climate fluctuation is another factor which affects local vegetation growth. In order to eliminate this influence, a background algorithm is applied. First, the buffer area around the heavy afflicted area is labeled as background area. And it is assumed that there is no obvious vegetation destruction which is caused by earthquake and other disturbance events there, so the climate fluctuation is the only factor that affects local vegetation in this background region. As the spatial variability of landform and the weather condition is significant in those mountain areas, too large buffer distance will probably result in different climate and vegetation condition between the buffer and the heavy afflicted area, which makes the elimination of climate fluctuation unreasonable. If the buffer distance is too small, the statistic analysis may not make sense. As the GPP difference map before earthquake (Fig. 2a) shows that the vegetation productivity capability in the buffer area and the heavy afflicted area is consistent, the buffer distance was chosen of 11,000 m. Then monthly mean GPP and reference monthly mean GPP maps are composed and averaged in the background area. The GPP values of labeled pixels are set to the same value as it mentioned above. After that, monthly $\Delta\mathrm{VPC_{bac}}$ values from January, 2008 to November, 2009 are calculated using the average of monthly mean GPP ($\mathrm{GPP_{bac}}$) and the average of reference monthly mean GPP ($\mathrm{GPP_{bacRef}}$) in the background area:

$$\Delta\mathrm{VPC_{bac}} = \left(1 - \frac{\mathrm{GPP_{bac}}}{\mathrm{GPP_{bacRef}}}\right) \times 100\%.$$

$\Delta\mathrm{VPC_{bac}}$ represents the vegetation productivity change on the effects of climate fluctuation. The negative value means the climate is favorable to vegetation growth, while a positive value shows the vegetation don't grow well in such a climate condition. So the climate fluctuation calibrated vegetation productive capability index (CFCVPC) is calculated as the sum of VPC and $\Delta\mathrm{VPC_{bac}}$:

$$\mathrm{CFCVPC} = \mathrm{VPC} + \Delta \mathrm{VPC}_{\mathrm{bac}}.$$

## 3 Results

### 3.1 Wenchuan earthquake's effect to local vegetation

The clear-sky MODIS GPP data after the earthquake (June 1 to June 8, 2008) is compared to the mean GPP value in the same period from 2004 to 2007 to evaluate the effects of the earthquake on local vegetation photosynthetic capability. The GPP difference map before the earthquake which is calculated by using clear-sky GPP images of May 1 to May 8, 2008 and corresponding mean GPP value from 2004 to 2007 in the same composite period is utilized to represent the vegetation condition before the earthquake.

Figure 2a is the GPP difference map before the earthquake, which is conducted by using clear-sky GPP data acquired just before the earthquake (May 1–8, 2008) and the reference GPP map (May 1–8, 2004–2007). As there may be bias of MODIS GPP products, the small value in the difference map is considered as unchanged. The 10 g C/m$^2$ is chosen as threshold value. If the GPP difference is less than 10 g C/m$^2$, it is assumed that the difference is slight and the local vegetation was growing normally compared to the former years. The slight difference in the picture means that local vegetation was growing normally compared to the former years before the earthquake. It is inferred that the climate fluctuation has little effect in vegetation in the study area before the disaster. Figure 2b shows the GPP variation after the earthquake. After the earthquake, vegetation in northwestern and southeastern counties in the study area grew well without obvious abnormality. Vegetation productivity decreased significantly along the seismic zone with the difference value larger than 10 g C/m$^2$, especially in northwestern Guangyuan, Jiange, Jiangyou, Anxian, Mianzhu, Shenfang, Pengzhou and Dujiangyan, as well as eastern Qingchuan, Pingwu, Beichuan, and, Wenchuan. So the local vegetation was destroyed along the seismic zone in the earthquake. The region which the difference larger than threshold value (10 g C/m$^2$) mainly distributed is sketched as the heavy afflicted area, which is along the seismic zone from Wenchuan to Qingchuan with an area of 8,287 km$^2$, while the background area is the buffer area with the distance of about 11,000 m around the heavy afflicted area (7,729 km$^2$) (Fig. 2b). In Fig. 2b, it can be found that there are some areas with positive difference GPP values, especially in northwest Beichuan and Maoxian. In fact, this region is far away from the earthquake fault zone which makes the effects of earthquake not as significant as in the seismic zone. There are fewer shocks with magnitude of more than 4.0 in this region (Fig. 2b), which means direct destruction and devastation wrought by the earthquake is not significant. In addition, fewer concomitant secondary geological hazards happened in this area. As these two main causes of vegetation destruction did not happened in this region, the vegetation here grew normally without obvious decrease.

Statistic analysis of GPP difference map after the earthquake shows that GPP dropped in an area of 21,139 km$^2$ (31% of the study area), with a total decrease of 0.205 Tg C (Table 1). The sum of the reference mean GPP from 2004 to 2007 is 1.734 Tg C, so the GPP dropped by 12% in the study area. The GPP difference map and the reference mean GPP map are then composed to the heavy afflicted area. The GPP decreased by 22% of the normal value in the heavy afflicted area with a total amount of 0.065 Tg C.

**Table 1** GPP decrease after Wenchuan earthquake

| GPP decrease (g C/m$^2$) | Area (km$^2$) | Area proportion (%) | Cumulative proportion (%) |
|---|---|---|---|
| >50 | 2 | 0.003 | 0.003 |
| 50–40 | 3 | 0.004 | 0.007 |
| 40–30 | 98 | 0.15 | 0.15 |
| 30–20 | 1,146 | 1.70 | 1.86 |
| 20–10 | 4,903 | 7.30 | 9.16 |
| 10–5 | 4,440 | 6.61 | 15.77 |
| 5–0 | 10,547 | 15.70 | 31.47 |

Gross Primary Productivity represents the photosynthetic capacity of vegetation. Vegetation mortality and damage are both factors which could decrease local GPP value. In the earthquake, fault slip will change the local geology environment of vegetation which could direct devastate or destruct local vegetation and diminish the carbon sink. Besides, concomitant secondary geological hazards, such as landslides and mudslides which are triggered by the earthquake resulted in vegetation mortality and burial. This is an effective way of transferring biomass from live to dead respiring pools especially over mountainous regions. After the earthquake, there are various situation of trees damage, such as buried and dead trees, fractured crowns, uprooted trees and stripped leaves. If trees are not buried, photosynthesis might still be active. However, its productivity capability will decrease, and the remote sensing products could capture these characters in time series observation.

### 3.2 Vegetation recovery after the earthquake

Monthly CFCVPC are calculated from January 2008 to November 2009 to evaluate local vegetation recovery condition. The Wenchuan earthquake broke out in May 12, 2008, so two CFCVPC values are calculated in May 2008. The first CFCVPC uses the GPP data from May 1–11, 2008. And the second CFCVPC is calculated using the GPP data from May 12–31, 2008. Figure 3 shows the time series of CFCVPC from January 2008 to November 2009. The green line means the vegetation productivity capability is the same as that of the normal years without obvious disturbance events. As the vegetation productivity is small in winter, the VPC and CFCVPC value in November, December, January and February will be largely influenced by the error of GPP data (dash blue line). So these time series data in winter is not used. As Fig. 3 shows, CFCVPC values in March, April and May before the earthquake (5B) in 2008 fluctuated around the green line (106% in March, 94% in April, 93% in May before the earthquake in 2008). However, the value dropped dramatically to 82% after May 12, 2008, when the Wenchuan earthquake broken out. It shows that the vegetation in the heavy afflicted area was intensively destroyed. Then the CFCVPC increased slowly, which shows that the local vegetation began to recover after the earthquake. In June 2008, the CFCVPC is 84%, which means that local vegetation productivity in heavy afflicted area is 84% of that of the normal value. The percentage increased to 87% in July 2008. Since August 2008, the vegetation productivity has been closed to normal level (101% in August, 94% in September, and 101% in October in 2008, and 109, 94, 91, 90, 98, 91, 90 and 104% from March to October in 2009 compared to the normal value). Long time series data is needed to monitor the local vegetation recovery.

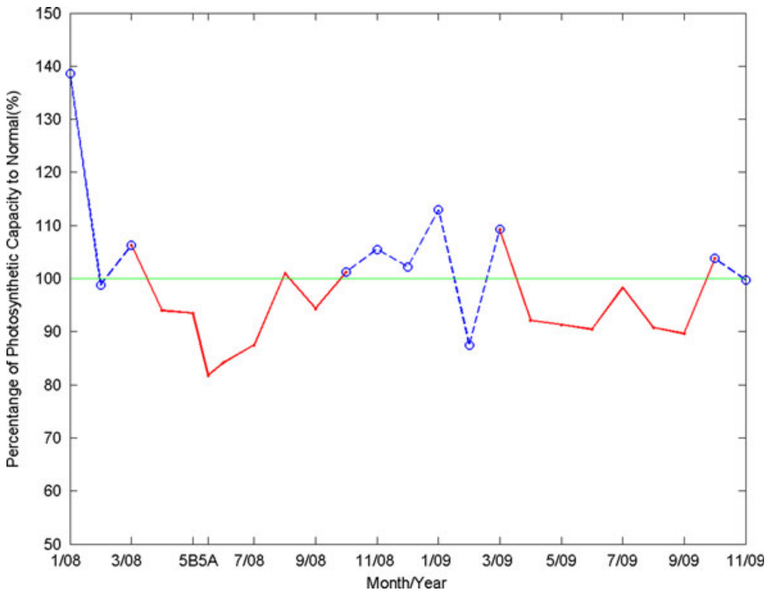


**Fig. 3** Time series of CFCVPC from January, 2008 to November, 2009. In May 2008, Two CFCVPC values are calculated. The first CFCVPC uses the GPP data before the earthquake from May 1 to May 11, 2008 (5B). And the second CFCVPC is calculated using the GPP data after the earthquake from May 12 to May 31, 2008 (5A). The vegetation productivity is small in winter and early spring (January, February, November and December), so the VPC and CFCVPC are largely influenced by the error of GPP data (*dash circle line*)

## 4 Discussion

Vegetation degradation mainly occurs along Longmenshan fault from Wenchuan to Qingchuan. Shocks, steep slope and the concomitant secondary geological hazards are the probable causes. By the time of 25 July, 2008, 19878 aftershocks had been monitored, in which 242 shocks are serious with the magnitude of more than Ms 4 (Chinese Seismic Information Site, http://www.csi.ac.cn/sichuan/index080512.htm). These aftershocks mainly occurred in middle-north Longmen Shan fault from Wenchuan to Qingchuan (Fig. 1). They changed local geology condition, and resulted in vegetation destruction.

Slope is another effective factor influencing vegetation mortality. According to Fig. 2b, we can find that vegetation degradation did not happen in all part along this shock frequent zone. In fact, the southwest part is heavily affected. This part, especially from Wenchuan to Mianzhu, is the steep slope region of the seismic zone (Fig. 4). The landslide is more probable to happen over a steep hillside than a flat surface.

After the earthquake and shakes, hundreds of landslides and debris flows happened. Vegetation as well as other objects will be destroyed by large-scale landslide and debris flow. Figure 5 shows the landslides distribution after Wenchuan earthquake. It can be found that landslides are mainly located along the seismic zone, especially from Anxian to Jiangyou. The epicenter, Wenchuan, is also a concentrated region. GPP change analysis proves that vegtetation in these region has been seriously affected after the disaster.

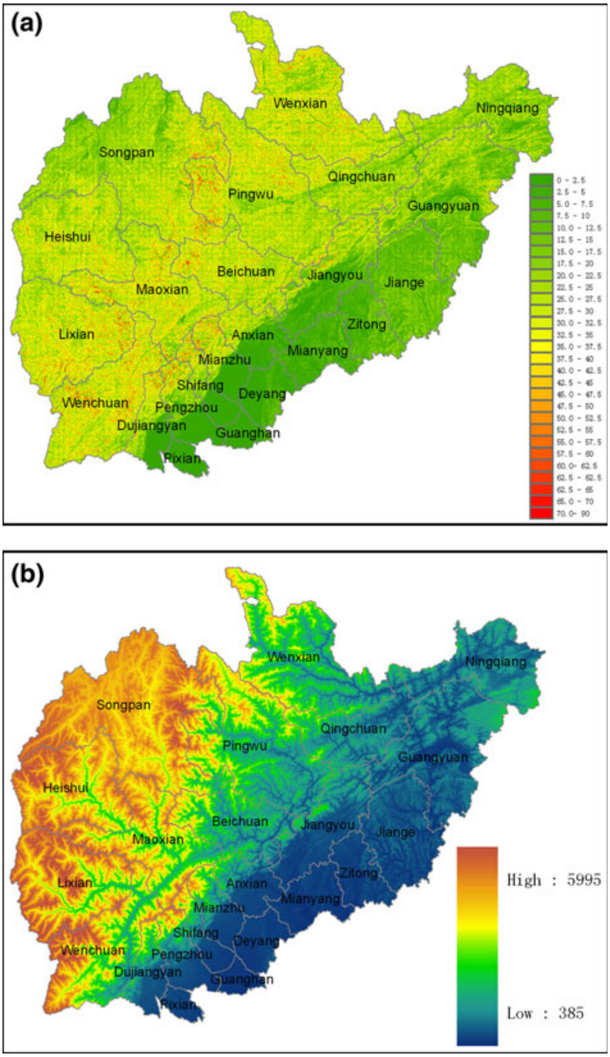


**Fig. 4** **a** Slope map of study area, **b** DEM map of study area

The vegetation productivity in heavy disaster area is close to normal level in 3 months later after the earthquake according to CFCVPC time series. However, it does not mean that local ecosystem has recovered. There are several situations in this vegetation damage, including downed and dead trees, snapped boles, fractured crowns, and stripped leaves (Chambers et al. 2007). Difference disturbances are various in the effects on local ecosystems. For example, anomalously warming decreases net ecosystem carbon dioxide exchange (NEE) by inducing drought that suppressed NPP in the extreme year and by stimulating heterotrophic respiration of soil biota in the subsequent year (Arnone et al. 2008; Phillips et al. 2009). Cyclone may cause uprooted, snapped, severe branch damage and minor damage which affect the structure and function of forest ecosystem, and species differed in the proportion of individuals within various damage extents (Chambers et al.

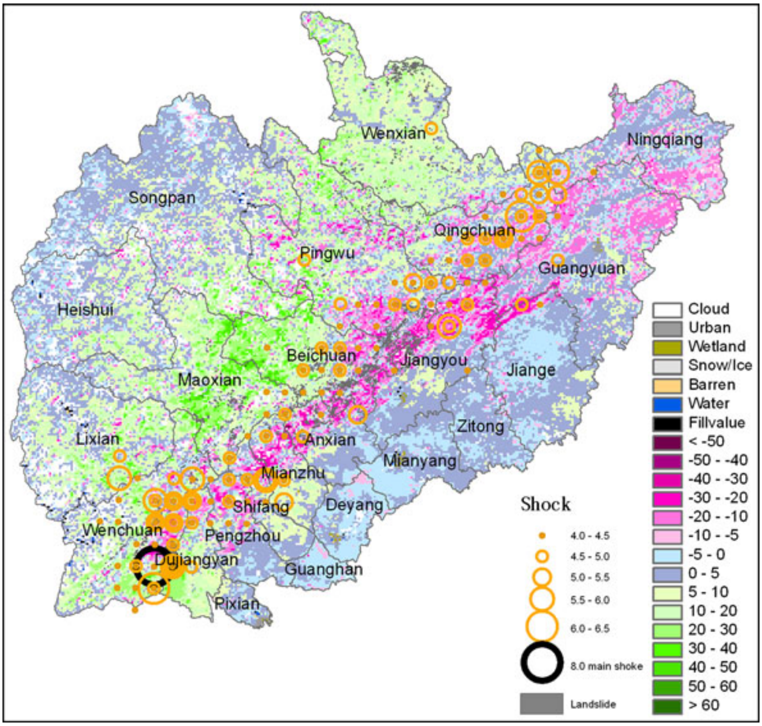


**Fig. 5** Geological hazards after the earthquake

2007; Curran et al., 2008; Turton 2008). Compared with other disturbances events, earthquake has different mechanism to affect trees. Earthquake would result in ground deformation, so there are many buried and dead trees after an earthquake but no snapped trees which can be found after Windthrow. When the disaster located in plain without severe geological change, the vegetation will have pleasant growth environment. So several years later, the ecosystem will probably recover. However, when the earthquake changed local geology environment, it will take longer period for the local ecosystem to recover due to the sequence soil and nutrient environment changes (Ren et al. 2009). In this situation, the ecosystem recovery will take a long period.

In the study area, the main landcover type is forest in northwest, while grassland and cropland in southeast. Different biome varies in recovery. The woody plants can't recover as quickly as the shrubs and herbs. As the earthquake broke out in May, the precipitation is abundant after the earthquake, and the radiation will be also increased for understory foliage as a result of trees damage. Thus, the shrubs and herbs recovered quickly which caused increase of GPP. However, the woody plants will take more time to recover. Thus, although the GPP has increased to near local normal level, it is probably that the trees and ecosystem vertical structure and function are not recovered. The ecosystem is still different from that before the disturbance. In the dry valley of the earthquake area, sparse shrub is the domain landcover type as lack of precipitation. So the effects of this region on GPP are not significant.

There are several uncertainties in vegetation recovery evaluation. Season is one uncertainty source. In late spring, summer and autumn, GPP value is large due to vegetation vigorous growth, so the effects of GPP error on VPC and CFCVPC calculation will be acceptable. However, when it comes to the winter and early spring, the vegetation productivity is small. So the VPC and CFCVPC value will be largely influenced by the error of GPP data. Cloud is another factor that affects the vegetation recovery evaluation. We can find that the CFCVPC values serious deviated from the green line in January 2008 and February 2009. The reason is that there were no clear-sky data during these months in large area. And, the vegetation productivity recovering to a normal level doesn't mean the ecosystem complete recovery, which need several years even several decades.

## 5 Conclusion

This study characterized the vegetation destruction and recovery after Wenchuan earthquake by MODIS GPP products and other ancillary GIS data. The results suggest that local vegetation GPP in the heavy afflicted area decreased by 22% compared to the mean value of the pervious 4 years along the seismic zone after the earthquake. Then the local vegetation began to recover after the earthquake (101% in August, 94% in September, and 101% in October in 2008, and 109, 94, 91, 90, 98, 91, 90 and 104% from March to October in 2009 compared to normal value).

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