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Sediment and hydrological response to vegetation recovery following wildfire on hillslopes and the hollow of a small watershed

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SUMMARY

Wildfire can cause dynamically spatial and temporal variations of hydrology and sedimentation from forested environments. The largest wildfire historically recorded in South Korea burned 23,484 ha of forest land in April 2000. In 2001, systems to monitor post-fire runoff and sediment were installed at the outlet of a small watershed and at seven plots on hillslopes of different vegetation condition. The hillslope and catchment responses were monitored for five years post-fire. The watershed was divided into four sites including terrace-sodding (TS), pine-planting and fast recovery (PF), pine-planting and slow recovery (PS), and hollow (H) according to treatment methods and topographical characteristic. The TS site showed the fastest vegetation recovery among the sites and the greatest reduction of soil erosion with time elapsed after wildfire. Sediment yield from the watershed as well as from plots depended strongly on rainfall erosivity index. While the runoff coefficient showed the highest correlation with rainfall amount, the sediment response rate had the strongest correlation with a vegetation index characterizing vegetation structure, litter, and root. The hollow mostly acted as a depositional zone but only contributed to erosion when it was disturbed by the treatment applications following the fire or during heavy rain following landslide activity in the catchment. These results indicate that gently-sloping hollow areas with rapidly recovering vegetation have the potential to reduce the flood and sediment risk. However heavy and extreme rainfall events during the study produced excessive sediment by catastrophic debris flow and landslide processes even on vegetated hillslopes. The study suggests that the boundary condition for whether (i) rain is heavy or extreme, (ii) surface condition is bare, and (iii) terrain has a deposition zone should be considered in order to evaluate sediment yields from burnt catchments.

1. Introduction

Wildfire frequency and severity have increased over the last three decades in many forest regions around the world (Conedera et al., 2003; Joint Fire Science Program, 2004; Cerdà and Lasanta, 2005; Park et al., 2005; Lane et al., 2006; Moody et al., 2013; Williams et al., 2013). Wildfires cause an enormous loss of forest resources and change the physicochemical properties of the soil (DeBano et al., 2005). A post-fire hillslope exposed by consumption of vegetation cover and the litter layer undergo erosion by direct raindrop impact and overland flow, whereas an unburned slope rarely experiences overland flow due to dense groundcover (Johansen et al., 2001; Smith and Dragovich, 2008). Numerous studies have indicated that the hydrologic and sediment responsesfollowing fire depend largely on the loss of groundcover (Simanton et al., 1990; Emmerich and Cox, 1994; Hester et al., 1997) which serves to increase infiltration and surface roughness, and reduce the kinetic impact of raindrops (Morgan, 1995). In particular, fire-removal of groundcover from water repellent soils reduces infiltration and enhances runoff generation and sediment transport (DeBano et al., 1998; Robichaud and Hungerford, 2000; Nyman et al., 2010). Therefore plant recovery and vegetation resilience are key factors to reduce soil erosion on burned hillslopes.

Fire effects on hydrological and geomorphological processes have been widely studied at the plot, hillslope and catchment scales (Mayor et al., 2007). Post-fire hydrologic and erosion processes acting across these scales exhibit spatial and temporal differences due to variations in vegetation, fire severity, weather, geological and topographical characteristics, and land management (Wondzell and King, 2003). Therefore, evaluation of fire effects for a given catchment requires experimental plots over multiple spatial scales.

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Experimental plot studies of small scales have shown that sediment yields and runoff rates from severely burned slopes were much greater than those from unburned and low-severity burnt slopes (Prosser and Williams, 1998; Benavides-Solorio and MacDonald, 2001; Pierson et al., 2001; Cerdà and Lasanta, 2005; Sheridan et al., 2007). Gimeno-García et al. (2007) found that regeneration of plant cover over an eight years period following burning greatly decreased soil losses from burned plots. Likewise, Cerdà (1998) found the runoff coefficient from simulated rainfall on severely burned plots was reduced from 45% six months following burning to 28% within 18 months and 6% within 5 and half years post-fire due mainly to the rate of vegetation recovery.

Hydrological responses to fire at the catchment scale have been studied less than those at small scales because of the difficulties of installing and maintaining instruments and the spatial heterogeneity of environmental factors (Shakesby and Doerr, 2006). Mayor et al. (2007) measured runoff and sediment yield in two burned and unburned catchments during the first seven years after a wildfire and found that wildfire impact on catchment runoff and sediment yield may be amplified by drought periods that delay plant recovery. Lane et al. (2006) re-instrumented the three catchments to collect high resolution discharge and sediment data from the burned area. Their study found a strong increase in sediment yield following fire and that the increase was driven primarily by erosion responses from two large rainfallevents.

Post-fire peak flow has received more attention than changes in total flow at catchment scales (Scott, 1993). The unit-area peak discharge is one of the sensitive hydrologic indicators of watershed response after a wildfire, especially in regions dominated by short-duration, high-intensity rainfall (Rowe et al., 1954; Robichaud et al., 2000; Smith et al., 2011b). Moody and Martin (2001) investigated rainfall-runoff relations for maximum 30-min rainfall intensities and unit-area peak discharges in three mountainous watersheds after wildfire and noted a decline in peak flow during a 3-year post-fire period.

Sediment yield tends to be high at small scales of bounded plots and are comparatively lower at catchment scales (Ferreira et al., 1997; Shakesby and Doerr, 2006) due to increasing storage capacity with increasing land area (Prosser and Williams, 1998). In particular, stream-head hollows, where surface flowlines from hillslopes converge (Kirkby and Chorley, 1967; Dunne and Black, 1970), are susceptible to surface runoff following storm events (Hack and Goodlett, 1960), but also may function as deposition storage areas to decrease catchment-scale sediment yield (Kirkby, 1994). The geomorphic function of hollows as depositional storage areasin burned catchments has rarely been evaluated.

In April 2000 a wildfire burned 23,484 ha in the Youngdong region on the east coast of South Korea. Hydrology, sediment, vegetation, and soil data were collected in a small catchment and on experimental plots for five years post-fire. Vegetation recovery at the study site was augmented with multiple re-vegetation treatments that varied across the site. Water discharge and sediment yields from differently treated plots were utilized to assess surface runoff and soil erosion from hillslopes in the small watershed. The objectives of the study are to evaluate the spatial and temporal response of sediment variations and hydrological processes on hillslopes and at the catchment scale, including the catchment hollow, associated with vegetation recovery after wildfire.

2. Material and methods

2.1. Site description

The East Coast wildfire in 2000 was recorded historically as the largest wildfire in South Korea. The fire intensity index as defined by Byram (1959) was estimated to range from 3000 to 7000 k W/m because nearly all of trees as well as the understory vegetation and ground cover were consumed by the fire. The dominant vegetation in this area changed from pines to oaks due to the wildfire (Lee, 2003). An experimental watershed of 0.682 ha is located in burnt mountain of Gangneung, South Korea (Fig. 1). The elevation ranges from 180 to 220 m between the coastline and the mountain range (37°48′49∼52″N and 128°48′19∼25″E) and includes an intermittent channel with a west to east flow direction. A topographical hollow, where surface flowlines converge, is located at center of the watershed. The soil is sandy with parental rocks originating from Mesozoic Jurassic granitic rocks (Kim et al., 2001).

The annual average temperature and humidity are 12 °C and 63.4%, respectively. The annual average rainfall recorded at Gangneung region by GRMA (Gangwon Regional Meteorological Administration) was 1,464 mm for the period from 1981 to 2010. Approximately 62% of the precipitation occurs during the summer season, June to September (Park and Shim, 1997). Rainfall is mainly associated with convective and orographic storms and typhoons. The annual rainfall of Gangneung during the study period (2001–2005) exceeded 1600 mm with exception of 2001 (1117 mm). Heavy rains at the site area associated with strong typhoons. The typhoon Rusa in 2002 was the largest rainfall event, with 24-h maximum rainfall of 880 mm and 1-h maximum rainfall intensity of 105 mm/h. The typhoon Maemi in 2003 was the second largest rainfallevent with 24-h maximum rainfall 301 mm and 1-h maximum rainfall intensity of 31 mm/h according to GRMA.

2.2. Monitoring

The study watershed was dominated by pine trees (*Pinus densiflora*) before fire. The damaged trees were cut down immediately after wildfire in 2000 and arranged parallel to slope-direction to prevent being washed downslope by floods. The mean height and dry weight of the burnt pine trees ($n = 51$) were 7.62 ± 1.33 m and 41.65 ± 24.50 kg, respectively. Two different treatments on the hillslopes were applied in 2001. Two-thirds of south-facing slopes where plant recovery was slow were treated by sodding of *Zoysia japonica* and spray seeding of *Arundinella hirta*, *Alnus hirsuta*, and *Lespedeza cyrtobotrya* after being terraced in April 2001 to decrease erosion and surface runoff (Lee, 2003). Other sites with the exception of the hollow site were planted with a young pine in September 2001 and managed periodically to help the growth of pine trees. No treatment was conducted in the hollow. Dominant species in the pine-planting site were *Quercus* spp., *Rhododendron* spp., *Lespedeza cyrtobotrya*, *Carex lanceolata*, *Smilax china*, *Miscanthus sinensis*, *Arumdinella hirta* as well as *Pinus densiflora*. Vegetation surveys were performed in July to August during which plant growth was steady. Six points were surveyed in 2001–2002 and ten in 2003–2005 to quantify the spatial distribution of plant spacing. Visual observation was used to measure the projected area of total coverage and coverage of each vegetation layer, such as herb,shrub, subtree, and tree, in 10 m × 10 m quadrates. The height of trees was measured manually. Field data including survey points, vegetation coverage, and vegetation height for six years is contained in an internal report (Park and Lee, 2007). Variations of vegetation condition for successive years after wildfire are presented in Fig. 2. Soil on the south-facing slope was exposed and disturbed by terrace-sodding treatment in April 2001, but exhibited rapid vegetation recovery. The rapid growth of *Alnus hirsute* at the terrace-sodding site was observed in June 2004 (Fig. 2). In September 2002, vegetation in the hollow was flattened down by heavy overland flow and covered by sediment from alandslide.

The experimental watershed was divided into four sites according to vegetation condition and topographical characteristics and