ARTICLE IN PRESS

Environmental Research ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Environmental Research

journal homepage: www.elsevier.com/locate/envres

The effects of future nationwide forest transition to discharge in the 21st century with regard to general circulation model climate change scenarios

Goro Mouri [a,*], Katsuhiro Nakano [b], Ikutaro Tsuyama [c], Nobuyuki Tanaka [c]

[a] Earth Observation Data Integration & Fusion Research Initiative (EDITORIA), The University of Tokyo, Be505, 4-6-1 Komaba, Meguro-ku, Tokyo 153-8505, Japan
[b] Department of Plant Ecology, Forestry and Forest Products Research Institute, Matsunosato 1, Tsukuba, Ibaraki 305-8687, Japan
[c] Hokkaido Research Centre, Forestry and Forest Products Research Institute, 7 Hitsujigaoka, Toyohira-ku, Sapporo, Hokkaido, Japan

ARTICLE INFO

Article history:
Received 26 February 2015
Received in revised form
7 January 2016
Accepted 18 January 2016

Keywords:
Climate change
Forest transition
GCM
Global warming
Hydrodynamic model
Rainfall runoff

ABSTRACT

Forest disturbance (or land-cover change) and climatic variability are commonly recognised as two major drivers interactively influencing hydrology in forested watersheds. Future climate changes and corresponding changes in forest type and distribution are expected to generate changes in rainfall runoff that pose a threat to river catchments. It is therefore important to understand how future climate changes will effect average rainfall distribution and temperature and what effect this will have upon forest types across Japan. Recent deforestation of the present-day coniferous forest and expected increases in evergreen forest are shown to influence runoff processes and, therefore, to influence future runoff conditions. We strongly recommend that variations in forest type be considered in future plans to ameliorate projected climate changes. This will help to improve water retention and storage capacities, enhance the flood protection function of forests, and improve human health. We qualitatively assessed future changes in runoff including the effects of variation in forest type across Japan. Four general circulation models (GCMs) were selected from the Coupled Model Intercomparison Project Phase 5 (CMIP5) ensemble to provide the driving fields: the Model for Interdisciplinary Research on Climate (MIROC), the Meteorological Research Institute Atmospheric General Circulation Model (MRI-GCM), the Hadley Centre Global Environment Model (HadGEM), and the Geophysical Fluid Dynamics Laboratory (GFDL) climate model. The simulations consisted of an ensemble including multiple physics configurations and different reference concentration pathways (RCP2.6, 4.5, and 8.5), the results of which have produced monthly data sets for the whole of Japan. The impacts of future climate changes on forest type in Japan are based on the balance amongst changes in rainfall distribution, temperature and hydrological factors. Methods for assessing the impact of such changes include the Catchment Simulator modelling frameworks based on the Minimal Advanced Treatments of Surface Interaction and Runoff (MATSIRO) model, which was expanded to estimate discharge by incorporating the effects of forest-type transition across the whole of Japan. The results indicated that, by the 2090s, annual runoff will increase above present-day values. Increases in annual variation in runoff by the 2090s was predicted to be around 14.1% when using the MRI-GCM data and 44.4% when using the HadGEM data. Analysis by long-term projection showed the largest increases in runoff in the 2090s were related to the type of forest, such as evergreen. Increased runoff can have negative effects on both society and the environment, including increased flooding events, worsened water quality, habitat destruction and changes to the forest moisture-retaining function. Prediction of the impacts of future climate change on water generation is crucial for effective environmental planning and management.

1. Introduction

Present-day climate change trends appear to show an increase in the probability of extreme weather events, the effects of which are harmful to towns, cities, agricultural land and infrastructure alike. Risk-based decision making for mitigation and adaptation

* Corresponding author.
E-mail address: mouri@rainbow.iis.u-tokyo.ac.jp (G. Mouri).

http://dx.doi.org/10.1016/j.envres.2016.01.024
0013-9351/

are essential from a climate risk management perspective. One particularly hazardous type of event is the summertime convective rainstorm, which can inundate mesoscale headwater catchments with water, causing flash flooding and crusting effects on the soil surface (Sivapalan and Blöschl, 1998; Bronstert, 2003; Valeo et al., 2003; Oki and Kanae, 2006; Zuber, 2007; Mouri et al., 2011, 2012, Zhang et al., 2011; 2013; Stella et al., 2013; Wu et al., 2015). Understanding and predicting the effects of climate change upon ecosystems is one of the grand challenges for global change scientists, and forecasting the impacts on forests is of particular importance (Hanson and Weltzin, 2000; Boisvenu and Running, 2006; Bonan, 2008; Singh, 2008; Yokoo et al., 2008; Mouri, 2015a). Experts have pointed out the future importance of potential changes in hydrological regimes caused by global climate change (Panagoulia and Dimou, 1997; Cameron et al., 2000; Schreider et al., 2000).

Forests, here broadly defined to include woodlands, cover 30% of the world's land surface (FAO, 2006). Around the globe, societies rely on forests for essential services such as timber and watershed protection and for less tangible but equally important recreational, aesthetic and spiritual benefits. Flood frequency is negatively correlated with the amount of remaining natural forest and positively correlated with loss of natural forest (Bradshaw et al., 2007). The effects of climate change on forests may be both positive and negative. Positive effects include increases in forest vigour and growth due to CO_2 fertilisation and increased water use efficiency, whereas negative effects include changes such as reduced growth, increased forest stress and mortality due to the combined impacts of climate change and climate-driven changes in the dynamics of forest insects (Scholes et al., 1995; Ayres and Lombardero, 2000; Bachelet et al., 2003; Galloway et al., 2003; LoehlE and LeBlanc, 1996; Lloyd and Bunn, 2007; Nakao et al., 2011; Stella et al., 2013).

Forests are subject to human influences such as increased ground-level precipitation and temperature (Fowler et al., 1999; Karnosky et al., 2005; Ollinger et al., 2008; Schoene and Bernier, 2012; Mouri et al., 2013). Although a range of responses can and should be expected, recent cases of increased tree mortality and die-offs triggered by drought and/or high temperatures raise the possibility that amplified changes to the type of forest distribution are already occurring in some locations in response to global climate change. Well-documented examples of this come from southern Europe (Peñuelas et al., 2001; Breda et al., 2006; Bigler et al., 2006, 2007; Somorin et al., 2012) and the temperate and boreal forests of western North America, where background forest mortality rates have increased rapidly in recent decades (Huntington, 2003; van Mantgem et al., 2009), and the widespread death of many tree species in a variety of forest types has affected well over 10 million ha since 1997 (Raffa et al., 2008). The common causal factors implicated in these examples are warmer temperatures and water stress, raising the possibility that the world's forests are increasingly responding to ongoing warming (Pimentel et al., 1995).

At present, climate prediction information for Japan is based on representative dynamic downscaling of the MIROC3.2 (hires) and MRI-CGCM2.3.2 models provided by the Coupled Model Intercomparison Project (CMIP5) based on the Special Report on Emissions (SRES) and the Representative Concentration Pathway (RCP) scenario (Nishii et al., 2009; Hanasaki et al., 2012). These models have been developed by the Meteorological Research Institute of the Domestic Research Organisation and have the advantage that additional detailed information about the whole of Japan is provided (Piani et al., 2010). The trend of precipitation during the 1990s was obtained from the Automated Meteorological Data Acquisition System (AMEDAS) of the Japanese Meteorological Agency.

Projections of future discharge that incorporate the effects of forest transition under global warming scenarios can provide stakeholders with estimates of possible future conditions. A number of models for water erosion have been developed in recent decades. Although their applicability varies with geographical setting, the models use common physical parameters (i.e., slope, precipitation, land cover and soil type), which have been found to be important from observation and multivariate statistical analyses (Siakeu and Oguchi, 2000; Dearing and Jones, 2003; Mouri et al., 2013). The study of discharge due to forest transition requires an investigation of the spatial variability of the factors affecting the erosion processes.

Recent developments in global observation by remote sensing have helped reveal the spatial distribution of vegetation. Using a digital elevation model (DEM), it is possible to extract topographical parameters from global geographic information system (GIS) data sets. Based on the FAO-UNESCO global digital soil map (FAO, 1995), global and Japanese data sets of soil properties have been made available by the Data and Information System (DIS), Digital National Information (DNI) framework of the International Geosphere–Biosphere programme (IGBP) and Forestry and Forest Products Research Institute (FFPRI) (Scholes et al., 1995; Walling and Fang, 2003; Mouri et al., 2013). These efforts have made assessment of soil erosion across Japan possible.

In this study, the Catchment Simulator modelling framework based on the MATSIRO model was employed to simulate average annual/monthly discharge incorporating the effects of forest transition on a 10-km mesh over the whole of Japan (Mouri et al., 2011, 2012, 2013; Mouri, 2015b). The numerical hydrodynamic model is a semi-distributed approach, which requires the breakdown of the study area into catchments and then further into landscape units within each catchment. The semi-distributed approach has physically interpretable parameters and combines the parametric efficiency of a combined approach with links to physical theory. Landscape units were expressed as homogeneous units within a catchment with uniform hydrological, soil, land use, and land-management properties (Takata et al., 2003). The annual discharge value of a 10-km grid refers to the average value of annual forest transition context values from different hillslopes in the grid, but it does not represent the amount of sediment leaving the grid. Therefore, the discharge estimated in this study is the potential value of discharge. The present research focused on Japanese discharge patterns and variation trends rather than absolute runoff amounts. The main objectives of this study were to describe present discharge potential in Japan, to analyse the trend of discharge over the past century and to project the long-term changes in discharge with reference to global climate change scenarios.

2. Theory and approach

2.1. Simulation approach

The modelling components considered were rainfall runoff, the effects on forest transition features across Japan and the impact of changing climate. One-dimensional simulations with modelled meteorological forces showed reasonable features in the monthly discharge incorporating the effects of forest transition in the twenty-first century. All water fluxes onto the ground surface were aggregated, and some portion of this water, depending on surface land cover, soil conditions and physical soil properties, became overland flow. Base flow was calculated using the simplified TOPMODEL scheme (Beven, 1997; Beven and Freer, 2001). Base flow originates from the layer in which the water table depth is defined, and the isotopic composition of the base flow is the same as the soil layer. Accordingly, the Catchment Simulator model was expanded to simulate hydraulic processes and forest transition in