DOI: 10.2478/frp-2018-0015
Available online: www.lesne-prace-badawcze.pl

Leśne Prace Badawcze / *Forest Research Papers*
Czerwiec / June 2018, Vol. 79 (2): 139–146

ORIGINAL RESEARCH ARTICLE

e-ISSN 2082-8926

Variability of hygro-climatic conditions of forest vegetation in Poland during the period of 1951–2015*

Mariusz Siedlecki

University Łódź, Faculty of Geographical Sciences, Department of Meteorology and Climatology, ul. Narutowicza 88, 90–139 Łódź, Poland

Tel. + 48 42 6655953, email: mariusz.siedlecki@geo.uni.lodz.pl

Abstract. This work presents an assessment of changes in the hygro-climatic conditions determining the vegetation and productivity of forest areas. Selected indices such as the radiant index of climate aridity – RIA, optimal precipitation – P_{opt}, critical value of precipitation – P_{krt} and CVP index (Climate, Vegetation, Productivity), which describe annual biomass and wood production under climatic conditions, were used. The analysis is based on standard meteorological measurements taken from 21 stations from the period of 1951–2015. The daily data were employed to calculate the previously mentioned indices, and the next linear trend coefficient was used to assess changes in hygro-climatic conditions.

The results show an increasing tendency towards dry climate conditions (positive values of the RIA linear trend coefficient) in a large part of the area consisting of Wielkopolska, the Silesian lowlands, and southern Poland. These areas are also characterized by the fastest increase in the most favourable sum of precipitation P_{opt} and critical precipitation P_{krt} for forest vegetation. This means that water resources in the environment and hygro-climatic conditions important for vegetation and the productivity of forest vegetation are deteriorating. On the other hand, the results of the CVP change assessment show an improvement in the climatic conditions influencing vegetation and forest productivity. The greatest positive changes of the CVP index are observed in the areas of south-eastern Poland.

Keywords: climate change, radiant index of climate aridity – RIA, optimal values of precipitation, critical values of precipitation, forest productivity

* The theses contained in this article were presented at the 3rd National Conference entitled 'The climatic conditions of forest life', organized by SGGW, Faculty of Forestry, at CEPL in Rogów on 1–3 June 2017.

1. Introduction

The growth of forest vegetation in Poland largely depends on water resources in the environment, shaped by atmospheric precipitation and evapotranspiration. A characteristic feature of Poland's climate is the predominance of evapotranspiration over precipitation, leading to a negative water balance in significant areas of the country (e.g., Danielak, Lenart 1989; Łabędzki et al. 2011). The formation of water resources is significantly affected by the radiation balance that determines the amount of available energy used in the process of evapotranspiration and the production of primary vegetation. Research in various types of environments indicates that in the conditions of limited energy resources, most of the available energy is used in the land evaporation process (principle of evaporation priority – Paszyński et al. 1995), limited by water resources (Kędziora 1999; Launiainen et al. 2005; Siedlecki et al. 2016).

In characterizing the hygro-climatic conditions of a specific area (including radiation conditions), the Radiant Index of Climate Aridity (RIA) is used, defined as the quotient of the annual radiation balance Rn and the energy needed to evaporate total annual rainfall LP_a (L – heat of evaporation, P_a – annual atmospheric precipitation) (Budyko 1975). RIA > 1 values corre-

Received: 17.11.2017, reviewed: 14.03.2018, accepted: 03.04.2018.

spond to dry climate conditions, where solar energy is sufficient to evaporate the occurring atmospheric precipitation. On the other hand, RIA values < 1 indicate moist climate conditions. In this case, the energy resources needed to evaporate precipitation are lacking, and therefore, a certain amount remains in liquid state (available for vegetation). Research has shown that with a given ratio of radiation and precipitation, the development of vegetation as well as its primary production are the greatest. The most favourable conditions for the development of forests are those areas with an RIA value of 0.8 (Budyko 1975). This means that at a specified value of the radiation balance, there is a certain amount of precipitation that is referred to as optimal precipitation P_{opt}. It is also possible to determine the precipitation value that fulfils the condition of RIA = 1, defined by the concept of critical precipitation P_{krt}, which is the necessary minimum for the functioning of forests in a given region.

The climate changes observed in the second half of the 20th and the beginning of the 21st century are having a significant impact both on the natural environment and on many aspects of human activity. In addition to the widely described global air temperature increase (IPCC 2007), attention is also being paid to the changes in atmospheric precipitation, solar radiation and evapotranspiration. These phenomena have a direct impact on the formation of moisture conditions important for the development of forest vegetation. For example, on the basis of measurements in the second half of the 20th century, there has been an increase in the value of the radiation balance (Abakumova et al. 1996), as well as in the values of solar radiation in Poland (Uscka-Kowalkowska et al. 2007). In papers devoted to the variability of precipitation in Poland, its increase has been noted in the spring and autumn season, with a simultaneous decrease of summer precipitation (Żmudzka 2002; Czarnecka and Nidzgorska-Lencewicz 2012). Zawora and Ziernicka (2003), based on the measurements from 1891–2000, found an increase in the annual precipitation in northern Poland, while the precipitation in central Poland showed a negative trend. Changes in the radiation balance and an increase in air temperature lead to the intensification of hydrological processes, with evapotranspiration as one of their most important elements. Both measurements and studies on changes in the process of evapotranspiration that take into account the climate models indicate an increase of global evapotranspiration in the period of 1982–2008 (Jung et al. 2010). Even more, a similar tendency is characteristic for climate simulations in the 21st century of various regions of the world (Abtew and Melesse 2013). This is also true for Poland, with Łabędzki et al. (2012) confirming an increase in the evapotranspiration indicator based on the observations conducted in 1970–2004 at the selected Polish meteorological stations. Jokiel (2007) drew attention to a similar tendency earlier and analysed the variability of potential evapotranspiration for the years of 1950–1990.

The abovementioned trends of changes are significantly important for the development of water resources under the conditions of climate change. They are all the more important given the fact that a negative climatic water balance is confirmed in the large areas of Poland (e.g., Rojek 2001; Bac, Rojek 2012) and observed atmospheric precipitation is lower than the values of optimal precipitation (Kożuchowski 2013a, b).

The main aim of this study is to assess the changes in the hygro-climatic conditions in Poland in the second half of the 20th and the beginning of the 21st century. In order to achieve this, the RIA index was used, and an assessment was made of the variability of optimal and critical rainfall values as well as the precipitation deficit for forest vegetation during the analysed period. In addition, the change in forest vegetation productivity was assessed based on the CVP (Climate, Vegetation, Productivity) index. The study can thus be seen as an attempt to supplement the existing studies on the spatial diversity of the RIA index, optimal precipitation and rainfall deficit in Poland (Kożuchowski 2013a, b). The results of this work may also broaden the discussion on changes in the hygro-climatic conditions in Poland, based on an assessment of the water balance (Rojek, Wiercioch 1995; Rojek 2001).

2. Materials and research methods

The work was based on standard meteorological measurements made at 21 meteorological stations (Figure 1) in Poland in the years 1951–2015, obtained directly from the Institute of Meteorology and Water Management – PIB. To achieve the aims of this study, the average daily value of air temperature, daily minimum and maximum temperature and the daily

Figure 1. Meteorological stations used in this work

totals of atmospheric precipitation were used. The collected data served to determine the monthly and annual averages, enabling the selected indicators to be specified, which characterize the conditions determining the growth and productivity of forest vegetation.

On the basis of the meteorological data collected, the values of the radiant index of climate aridity were determined, which takes into account the changes in the radiation balance as well as changes in the annual atmospheric precipitation.

It is defined as:

$$RIA = \frac{R_n}{LP_a},$$

where:
R_n – radiation balance,
P_a – total annual atmospheric precipitation,
L – latent heat.

Radiation balance R_n is defined as the difference between the net short-wave radiation R_{ns} and the net long-wave radiation R_{nl}. Measurements of all components of the radiation balance are not performed at each meteorological station; they are usually multiple-year measurement series (Kożuchowski 2013b), therefore, in many studies (e.g., Miara et al. 1987; Paszyński et al. 1995), a series of empirical equations to determine the radiation balance were commonly used, whose parameters are air temperature, degree of cloud cover, or also water vapor pressure (Kędziora 1999). The present study used the same procedure and the values of radiation balance were determined on the basis of standard meteorological measurements.

First, solar radiation at the upper limit of the atmosphere R_a was determined with the equation:

$$R_a = \frac{24(60)}{\pi} G_{sc} d_r [\omega_s \sin(\varphi)\sin(\delta)] + \cos(\varphi)\cos(\delta)\sin(\omega_s),$$

where:
G_{sc} – solar constant,
d_r – Earth-Sun distance for successive days in the year,
ω_s – hourly angle of the Sun,
φ – latitude,
δ – declination of the Sun.

The individual components of the equation were determined according to specified formulas described in detail in Allen et al. (1998).

The calculated values of R_a and the measured daily values of maximum and minimum temperature allowed (based on the Hargreaves' formula) the intensity of solar radiation R_s on the surface of the Earth to be determined (Allen et al. 1998):

$$R_s = k_{Rs}\sqrt{(T_{max} - T_{min})}R_a,$$

where:
T_{max} – daily maximum temperature,
T_{min} – daily minimum temperature,
k_{Rs} – coefficient taking into account the distance of the station from the sea.

Net short-wave radiation R_{ns} was determined with the equation:

$$R_{ns} = (1 - \alpha)R_s,$$

where:
α – albedo (an average value of 0.23 was assumed in this work)

The final element of the radiation balance is the net long-wave radiation, which was calculated using the formula (Allen et al. 1998):

$$R_{nl} = \sigma\left[\frac{(T_{max})^4 + (T_{min})^4}{2}\right]\left(0.34 - 0.14\sqrt{e_a}\right)\left\{1.35\frac{R_s}{R_{so}} - 0.35\right\},$$

where:
σ – the Stefan-Bolzmann constant,
e_a – actual water vapor pressure,
R_{so} – radiation under a cloudless sky, calculated as:

$$R_{so} = (0.75 + 2 \cdot 10^{-5}z)R_a,$$

where:
z – height a.s.l. of the station.

The value of water vapor pressure was calculated based on the equation:

$$e_a = 0.611\, exp\left[\frac{17.27\, T_{min}}{T_{min} + 237.3}\right].$$

In addition to the radiant index of climate aridity, the R_n values also allowed the next indicators to be determined, that is, P_{opt} and P_{krt}.

The optimal P_{opt} precipitation corresponds to a value of RIA = 0.8, that is, this is the amount of precipitation for which the largest increases in the biomass of green plants are recorded:

$$P_{opt} = \frac{R_n}{0.8L}.$$

On the other hand, the value of critical precipitation P_{krt} corresponds to RIA = 1, that is, it specifies the necessary minimum amount of moisture in the climate for the growth of forest vegetation:

$$P_{krt} = \frac{R_n}{L}.$$

Precipitation deficit D is defined as:

$$D = P_a - P_{krt}.$$

The collected measurement data and designated indicators of hygro-climatic conditions allow changes to be assessed of the potential, climate-conditioned productivity of forests. For this purpose, the *CVP* index (*Climate, Vegetation, Productivity*) by Paterson (1956) was used (after Kożuchowski 2014):

$$CVP = 0.01\,(TP_aGE)/12A,$$

where:
T – mean monthly temperature of the warmest month,

P_a – total annual precipitation,
G – number of months in which the mean monthly temperature exceeded 3°C,
E – function of the latitude describing the influence of day length on vegetation growth,
A – amplitude of annual air temperature.

The obtained series of selected hygro-climatic indicators were then used to determine the linear trend coefficient in the analysed period. The Mann-Kendall test (for a significance level of 0.05) and an analysis of the values of the determination coefficient were used to test the significance of the trend.

In order to achieve a better spatial differentiation in the area of Poland, geostatistical interpolation – ordinary kriging was used, which allows an approximate presentation to be made of the results of the variability assessment of the selected hydro-climatic indicators.

3. Results

In the first stage of determining the characteristics of the variability of hygro-climatic conditions in Poland in 1951–2015, comparisons were made of the course of the analysed variables as anomalies of the annual average values in the surveyed multiple year period. This approach to the problem allows us to show not only the trends of the increase/decrease of the analysed variables, but also indicates the years, pentads or decades characterized by the clearly higher or lower values in the analysed period. Due to the limitations on the size of this article, the issues presented are discussed using the example of a meteorological station located in the south-western part of Łódź at the Łódź Lublinek airport (Figure 2).

The obtained results indicate an increase in the value of the radiation balance in the analysed period, and the last two decades of the 20th century and the beginning of the 21st century are years with relatively high positive anomalies of R_n values (Fig. 2a). The comparison of the annual anomaly of P_a (Figure 2b) and the RIA index (Figure 2c) clearly shows that atmospheric precipitation is a factor determining the course of the RIA values. Dry periods, such as the years 1985–1993, when the RIA index reached a value higher than 1, overlap with years with negative anomalies of annual precipitation. Another pentad (1995–2000) is characterized by relatively high precipitation, which results in lowering the RIA value. The course of the anomalies of annual P_{opt} (Fig. 2d), in accordance with the definition of this parameter, shows a clear correlation with the course of the radiation balance anomaly. This means a deterioration in water resources, and thus, more difficult conditions for the growth of forest vegetation, while years with high values of annual radiation balance are also distinguished by high values of optimal precipitation.

This is also confirmed by the trends seen in the atmospheric precipitation deficit D. An increasing value of optimal precipitation, with unchanged totals of annual precipitation, increasingly leads to the conditions that do not provide the necessary minimum moisture in the climate needed for the best development of forest vegetation. The course of anomalies in the annual precipitation deficit (Fig. 2e) against the background of the other analysed values shows that atmospheric precipitation

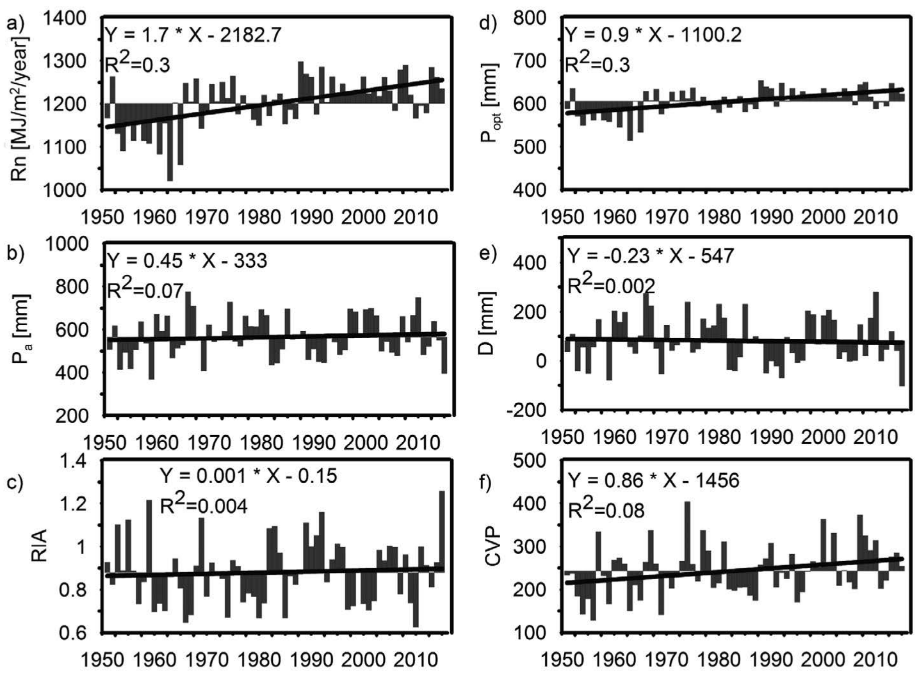

Figure 2. The course of annual anomalies of selected meteorological parameter in Łódź during the period 1951–2015. (Rn – radiation balance, Pa – annual precipitation, RIA - index of climate aridity, Popt - optimal precipitation, D – precipitation deficit, CVP – index Climate, Vegetation, Productivity)

is a decisive element in the characteristics of changes in hygro -climatic conditions. It is in the years of relatively low annual precipitation that small precipitation deficits are present. Also, the course of the CVP index anomaly has relatively high values occurring in years with large annual precipitation totals, even though it takes into account both changes in atmospheric precipitation and thermal conditions (Fig. 2f).

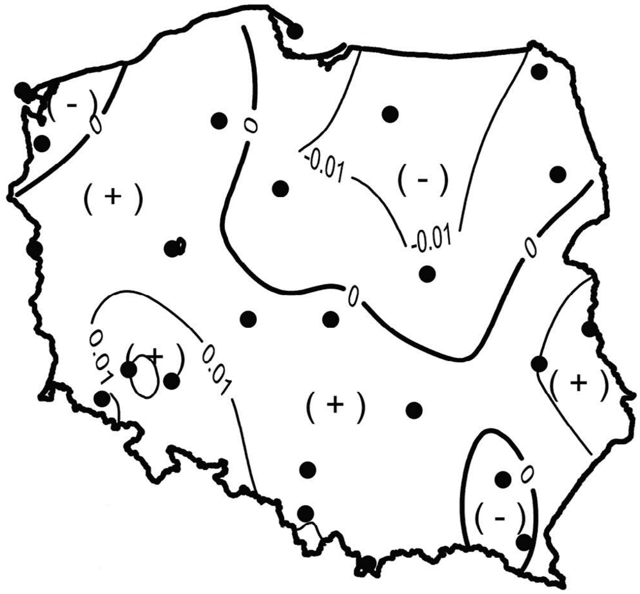

Figure 3. The spatial distribution of trend coefficient of the radiant index of aridity RIA (per decade) during the years 1951–2015

The directions of change in the selected hygro-climatic conditions, shown on the example of one meteorological station located in Łódź, and having a direct impact on forest vegetation growth, were observed at most of the analysed stations. The spatial differentiation of these changes is presented on the maps showing the distribution of the linear trend coefficient of the selected indicators. The obtained values of the linear trend in most cases are very low and not statistically significant. However, using this approach allows us to answer the question about the directions of change for the analysed conditions against the background of climate change.

Most of Poland (except for Wielkopolska, the Mazovian Lowland and the Lublin Upland) is characterized by an average value of RIA < 1. The research conducted on the changes in this indicator makes it possible to distinguish two zones in Poland. In the spatial distribution of the stations in north-eastern Poland, improvements in the hygro-climatic conditions are noticeable (a negative RIA coefficient), while in significant areas of lowland Poland and the Lublin Upland, positive RIA values indicate an increase in the aridity of the climate (Figure 3), where the trend values are very low.

The tendencies of change in optimal as well as critical precipitation are largely dependent on changes in the radiation balance. The highest values of the trend are found in areas of south-eastern Poland. At the Lublin, Rzeszów and Włodawa stations, trend values indicate an average increase

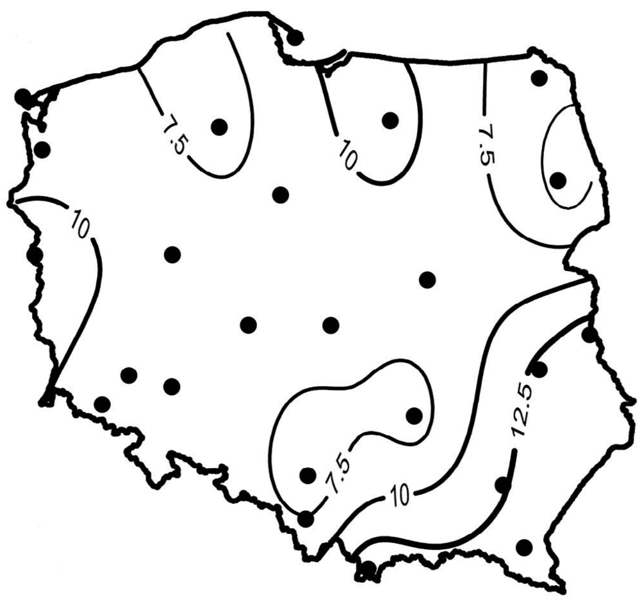

Figure 4. The spatial distribution of trend coefficient of the optimum values of annual precipitation P_{opt} (mm/decade) during the years 1951–2015

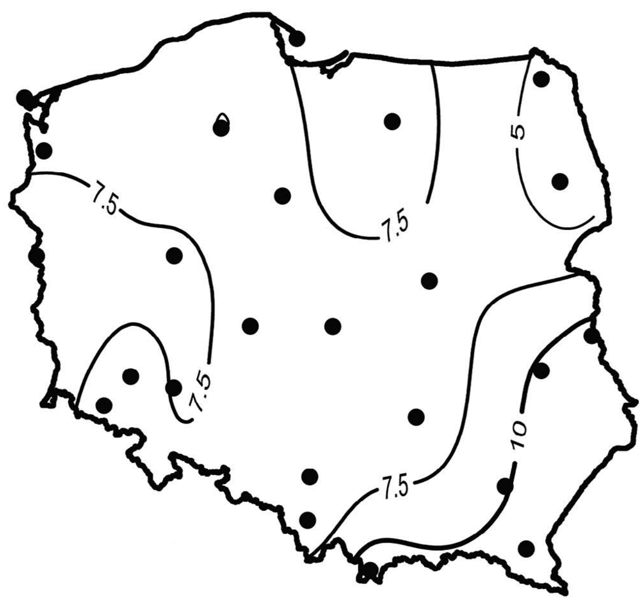

Figure 5. The spatial distribution of trend coefficient of the critical values of annual precipitation totals P_{krt} (mm/decade) during the years 1951–2015

of over 12 and 10 mm/decade of optimal rainfall and critical rainfall respectively (Figures 4 and 5).

In southern and south-eastern Poland, a trend was noted of an increase in the climate aridity, and changes in the critical precipitation, significantly important in shaping water resources. For example, the highest increase in critical precipitation in the Lublin Upland leads to an ever smaller difference between P_a and P_{krt}, that is, the value of the precipitation deficit (Figure 6). Thus, changes occurring in the hygro-climatic conditions that are influenced by an increase in the radiation balance mean that the observed trend in atmospheric precipitation is approaching the limit determining the zone of a dry climate (RIA > 1), which hinders the growth of forest vegetation. A negative trend in the difference between atmospheric precipitation and critical rainfall has been recorded at many meteorological stations in central Poland and Upper and Lower Silesia. The results confirm the deterioration of the hygrometric conditions in the region, which in light of many studies is distinguished by a negative water balance (Rojek, Wiercioch 1995; Rojek 2001; Łabędzki et al. 2012) and a negative trend for annual precipitation (Zawora, Ziernicka 2003). On the other hand, in the north-east of Poland, where the results of the research indicated a decrease in the climate aridity index, we also have a positive trend for the atmospheric precipitation deficit. An increase in $P_a - P_{krt}$ difference translates into conditions in which the occurring precipitation is enough to meet the demand for potential evapotranspiration and also serves as a resource for vegetation growth.

Figure 6. The spatial distribution of trend coefficient of the annual deficits of observed precipitation totals D (mm/decade) during the years 1951–2015

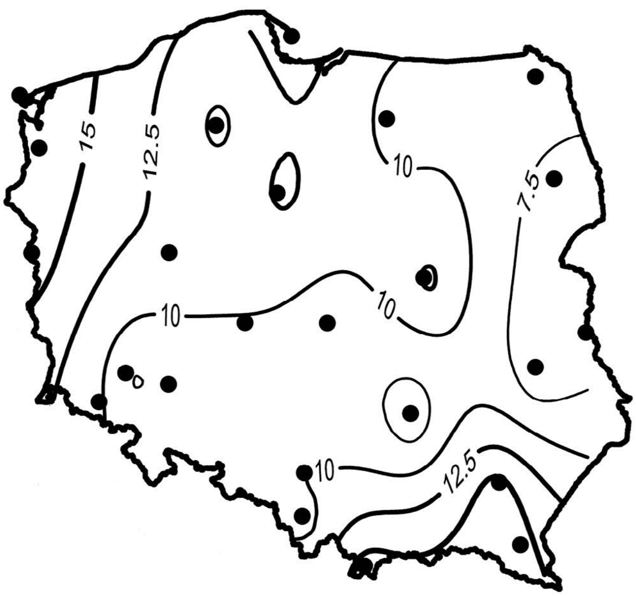

Figure 7. The spatial distribution of trend coefficient of CVP index (per decade) during the years 1951–2015

In addition to the precipitation and radiation balance, the conditions for forest vegetation growth, and thus the conditions for increases in tree mass, are also formed by thermal conditions. These factors are taken into account by the CVP index used in the study. The higher the value of this index, the better the conditions for forest productivity. The results of the assessment of the change trends of this parameter indicate an increase in the conditions for forest productivity under the conditions of climate change at all analysed stations. The highest positive changes in the CVP index were found for the Podkarpacie region and north-western Poland, which are characterized by one of the better conditions for the development of forest vegetation (Figure 7).

4. Summary and discussion

The conducted assessment of changes in hygro-climatic conditions (in the period of 1951–2015), affecting the vegetation and productivity of forest vegetation, shows:

• an increase in climate aridity (increase in the RIA value) in the areas of Wielkopolska, Lower Silesia and the highlands,

• a decrease in the RIA value for stations located in north-eastern Poland and partly in Mazovia,

• an increase in the value of optimal and critical precipitation for the growth of forest vegetation – the highest occurring in south-eastern Poland,

• an increase in the CVP index, which means an improvement in growth conditions and forest vegetation productivity.

At the same time, it should be emphasized that at most stations, the above-mentioned trend values of the analysed variables assume very small values that are not statistically significant.

The obtained results indicate a deterioration of the hygro-climatic indicators, and thus – the conditions for the development of forest vegetation. The factor of limited water resources is most often indicated as the reason for a reduction in the growth of forest vegetation in various regions of the world (Allen et al. 2010; Milad et al. 2011) as well as in Poland (e.g., Wawrzoniak et al. 2017). Climate change, manifested by an increase in the frequency of heat waves and periods of drought, is indicated as the reason for the lower annual growth increases in the forests of north-eastern France (Charru et al. 2010) or the dying out of pedunculate oak (Siwecki, Ufnalski 1998) in Poland or spruce in southern Norway (Solberg 2004) and Poland (e.g., Paluch 2015; Jaworski and Pach 2013). A consequence of the deteriorating health condition of trees as a result of drought also results in an increase in the number of forest fires and pest infestations (Szczygieł et al. 2008; Szczygieł et al. 2009).

On the other hand, when considering additional meteorological factors determining the growth of forest vegetation that are taken into account by the CVP index used, an increase is shown in the conditions of forest productivity in the analysed period. It is worth emphasizing that the indicated tendency is the strongest in the area of the Lakeland belt, the Silesian Lowland and the highlands belt, where the average CVP index values are the highest (Kożuchowski 2014).

Climate change, apart from changes in temperature and precipitation, is also an increase in the concentration of carbon dioxide in the atmosphere. This leads to an increased intensity of photosynthesis, whereas a faster rate of sequestration by forest vegetation requires the existence of appropriate water resources in the environment. On the other hand, with higher concentrations of CO_2 in the atmosphere, the rate of the water use efficiency of plants increases, defined as the ratio of the carbon dioxide stream to the water vapor stream (Lindner et al. 2014; Keenan et al. 2013). This process may limit the negative effects of an increasing shortage of precipitation on forest productivity.

Acknowledgment and source of funding

The research was financed from the resources of the Department of Meteorology and Climatology, Faculty of Geographical Sciences, University of Łódź.

Conflict of interest

The author declares no potential conflicts of interest.

References

Abakumova G.M., Feigelson E.M., Russak V., Stadnik V.V. 1996. Evaluation of long-term changes in radiation, cloudiness, and surface temperature on the territory of the Former Soviet Union. *Journal of Climate* 9: 1319–1327. DOI 10.1175/1520-0442(1996)009<1319:EOLTCI>2.0.CO;2.

Abtew W., Melesse A. 2013. Evaporation and Evapotranspiration: Measurements and Estimations. Springer, Dirdrecht-Heidelberg-New York-London, 206 s. ISBN 978-94-007-4736-4.

Allen C.D., Macalady A.K., Chenchouni H., Bachelet D., McDowell N., Vennetier M. et al., 2010. A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. *Forest Ecology and Management* 259(4): 660–684. DOI 10.1016/j.foreco.2009.09.001.

Allen R.G., Pereira L.S., Raes D., Smith M. 1998. Crop evapotranspiration – Guidelines for computing crop water requirements. *FAO Irrigation and Drainage Paper* 56, FAO – Food and Agriculture Organization of the United Nations, Rome, 15 s. ISBN 92-5-104219-5.

Bac S., Rojek M. 2012. Meteorologia i klimatologia w inżynierii środowiska, wyd. 2, Wydawnictwo Uniwersytetu Przyrodniczego we Wrocławiu, Wrocław, 276 s. ISBN 978-83-7717-112-7.

Budyko M.I. 1975. Klimat i życie. PWN, Warszawa, 526 s.

Charru M., Seynave I., Morneau F., Bontemps J.-N. 2010. Recent changes in forest productivity: an analysis of national forest inventory data for common beech (*Fagus sylvatica* L.) in north-eastern France. *Forest Ecology and Management* 260(5): 864–874. DOI 10.1016/j.foreco.2010.06.005.

Czarnecka M., Nidzgorska-Lencewicz J. 2012. Wieloletnia zmienność sezonowych opadów w Polsce. *Woda-Środowisko-Obszary Wiejskie* t. 12, z. 2(38): 45–60. ISSN 1642-8145.

Danielak D., Lenart W. 1989. Wyznaczanie parowania terenowego w Polsce metodą kompleksową. Roczniki Akademii Rolniczej w Poznaniu CCI, Melioracje 8: 41–51. ISSN 0208-8932.

IPCC 2007. WGI fourth assessment report to climate change: the physical science basis; summary for policymakers. Intergovernmental Panel on Climate Change IPCC, Geneva. ISBN 978-0-521-88009-1 hardback, ISBN 978-0-521-70596-7 paperback.

Jaworski A., Pach M. 2013. Zmiany udziału buka, jodły i świerka w dolnoreglowych drzewostanach naturalnych w rezerwacie "Dolina Łopusznej (Gorczyński Park Narodowy)". *Sylwan* 157 (3): 213–222. ISSN 0039-7660.

Jokiel P. 2007. Zmiany, zmienność i ekstremalne sumy parowania terenowego i ewapotranspiracji potencjalnej w Łodzi w drugiej połowie XX wieku. *Acta Universitatis Lodziensis. Folia Geographica Physica* 8: 63–88.

Jung M. et al. 2010. Recent decline in the global land evapotranspiration trend due to limited moisture supply. *Nature* 467: 951–954. DOI 10.1038/nature09396.

Keenan T.F., Hollinger D.Y., Bohrer G., Dragoni D., Munger J.W., Schmid H.P., Richardson A.D. 2013. Increase in forest water-use efficiency as atmospheric carbon dioxide concentrations rise. *Nature* 499: 324–327. DOI 10.1038/nature12291.

Kędziora A. 1999. Podstawy agrometeorologii. Państwowe Wydawnictwo Rolnicze i Leśne, Poznań, 364 s. ISBN 83-09-01641-7.

Kożuchowski K. 2013a. Ocena higroklimatycznych warunków wegetacji w Polsce. *Monitoring Środowiska Przyrodniczego* 14: 103–111. ISSN 1734-6762.

Kożuchowski K. 2013b. Saldo promieniowania i higroklimatyczne warunki wegetacji w Polsce. *Przegląd Geo izyczny* LVIII (1–2): 41–54. ISSN 0033-2135.

Kożuchowski K. 2014. Meteorologia i klimatologia dla studentów leśnictwa. Wydawnictwo Uniwersytetu Łódzkiego, Łódź, 370 s. ISBN 978-83-7969-414-3.

Launiainen S., Rinne J., Pumpanen J., Kulmala L., Kolari P., Keronen P., Siivola E., Pohja T., Hari P., Vesala T. 2005. Eddy covariance measurement of CO_2 and sensible and latent heat fluxes during a full year in a boreal pine forest trunk-space. *Boreal Environment Research* 10: 569–588. ISSN 1239-6095.

Lindner M., Fitzgerald J.B., Zimmermann N.E., Reyer C., Delzon S., van der Maaten E, Schelhaas M.-J., Lasch P., Eggers J., van der Maaten-Theunissen M., Suckow F., Psomas A., Poulter B., Hanewinkel M. 2014. Climate change and European forests: What do we know, what are the uncertainties, and what are the implications for forest management? *Journal of Environmental Management* 146: 69–83. DOI 10.1016/j.jenvman.2014.07.030.

Łabędzki L., Bąk B., Kanecka-Geszke E. 2012. Wielkość i zmienność ewapotranspiracji wskaźnikowej według Penmana-Monteitha w okresie wegetacyjnym w latach 1970-2004 w wybranych rejonach Polski. *Woda-Środowisko-Obszary Wiejskie* t. 12, z. 2(38): 159–170.

Łabędzki L., Kanecka-Geszke E., Bak B., Slowinska S. 2011. Estimation of Reference Evapotranspiration using the FAO Penman-Monteith Method for Climatic Conditions of Poland, in: Łabędzki L. (ed.), Evapotranspiration. InTech, 275–294. DOI 10.5772/14081.

Miara K., Paszyński J., Grzybowski J., 1987. Zróżnicowanie przestrzenne bilansu promieniowania na obszarze Polski. *Przegląd Geograficzny* 59(4): 487–509. ISSN 0033-21-43.

Milad M., Schaich H., Bürgi M., Konold W. 2011. Climate change and nature conservation in Central European forests: A review of consequences, concepts and challenges. *Forest Ecology and Management* 261(4): 829–843. DOI 10.1016/j.foreco.2010.10.038.

Paluch R. 2015. Wieloletnie zmiany składu gatunkowego drzewostanów naturalnych w Puszczy Białowieskiej. *Sylwan* 159 (4): 278–288. ISSN 0039-7660.

Paszyński J., Kędziora A., Tuchołka S., Kapuściński J., Olejnik J. 1995. Wpływ rodzaju powierzchni czynnej na strukturę bilansu cieplnego, w: Krawczyk B., Błażejczyk K. (red.), Współczesne badania klimatologów polskich w kraju i za granicą. Sympozjum klimatologiczne z okazji 40-lecia Zakładu Klimatologii IGiPZ PAN, Radzików, 7–8 listopada 1994 r. Conference Papers 23. Instytut Geografii i Przestrzennego Zagospodarowania PAN, Warszawa, 69–92.

Paterson S.S. 1956. The forest area of the world and its potential productivity. Royal University of Göteborg, 216 s.

Rojek M. 2001. Klimatyczny bilans wodny Polski w okresie 1961–1995. Plansza 27, w: Koźmiński Cz., Michalska B., Atlas klimatyczny ryzyka upraw roślin w Polsce. Akademia Rolnicza w Szczecinie, Uniwersytet Szczeciński, Szczecin.

Rojek M., Wiercioch T. 1995. Zmienność czasowa i przestrzenna parowania wskaźnikowego, ewapotranspiracji aktualnej i niedoboru opadów w Polsce nizinnej w okresie 1951-1990. Zeszyty Naukowe Akademii Rolniczej we Wrocławiu, Monografie 6, 238, 51 s.

Siedlecki M., Pawlak W., Fortuniak K., Zieliński M. 2016. Wetland evapotranspiration: Eddy covariance measurement in the Biebrza valley, Poland. *Wetlands* 36(6): 1055–1067. DOI 10.1007/s13157-016-0821-0.

Siwecki R., Ufnalski K. 1998. Review of oak stand decline with special reference to the role of drought in Poland. *European Journal of Forest Pathology* 28(2): 99–112. DOI 10.1111/j.1439-0329.1998.tb01171.x.

Solberg S. 2004. Summer drought: a driver for crown condition and mortality of Norway spruce in Norway. *Forest Pathology* 34(2): 93–104. DOI 10.1111/j.1439-0329.2004.00351.x.

Szczygieł R., Ubysz B., Piwnicki J. 2008. Wpływ zmian klimatycznych na kształtowanie się zagrożenia pożarowego lasów w Polsce. *Leśne Prace Badawcze* 69 (1): 67–72. ISSN 1732-9442.

Szczygieł R., Ubysz B., Kwiatkowski M., Piwnicki J. 2008.Klasyfikacja zagrożenia pożarowego lasów Polski. *Leśne Prace Badawcze* 70 (2): 137–141. DOI 10.2478/v10111-009-0013-2.

Uscka-Kowalkowska J., Przybylak R.,Vizi Z., Araźny A., Kejna M., Maszewski R. 2007. Variability to global solar radiation in Central Europe during the period 1951–2005 (on the basis of data from NCEP/NCAR reanalysis project). *Geographica Polonica* 80(2): 59–68. ISSN 0016-7282.

Wawrzoniak J., Boczoń A., Hildebrand R., Kantorowicz W., Kluziński L., Kowalska A., Lech P., Małachowska J., Piwnicki J., Szczygieł R., Ślusarski S., Zajączkowski G. 2017. Stan uszkodzenia lasów w Polsce w 2016 roku na podstawie badań monitoringowych. Instytut Badawczy Leśnictwa, Zakład Zarządzania Zasobami Leśnymi. Sękocin Stary.

Zawora T., Ziernicka A. 2003. Precipitation variability in time in Poland in the light of multi-annual mean values (1891–2000). *Acta Universitatis Wratislaviensis* 2542, Studia Geograficzne 75: 123–128.

Żmudzka E. 2002. O zmienności opadów atmosferycznych na obszarze Polski nizinnej w drugiej połowie XX wieku. *Wiadomości IMGW* 25(46), z. 4: 23–38. ISSN 0208-6263.

Translated by: Barbara Przybylska