Seasonal differences in runoff between forested and non-forested catchments: a case study in the Spanish Pyrenees

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Abstract The hydrological response of two neighbouring catchments in the central Spanish Pyrenees with similar lithology and topography but different land use was compared. One catchment (2.84 km^2) was extensively cultivated in the past, and the other (0.92 km^2) is covered by dense natural forest. Differences in runoff were strongly related to catchment wetness conditions and showed a marked seasonality: under dry conditions runoff tended to be greater in the former agricultural catchment, whereas under wet conditions it tended to be greater in the forested catchment. One explanation for this switching behaviour could be an increase in the hydrological connectivity within the slopes of the forested catchment as it becomes wetter, which favours the release of large amounts of subsurface flow. Differences in land use (vegetation and soil properties) dictate the contrasting dominant runoff generation processes operating in each catchment, and consequently the differences between their hydrological responses.

Key words water yield; seasonal controls; hydrograph characteristics; forested catchment; land use/land cover change; experimental catchment; sub-Mediterranean mountains

INTRODUCTION

Mediterranean mountains are largely affected by land abandonment and subsequent vegetation recovery with significant hydrological consequences (e.g. García-Ruiz & Lana-Renault, 2011). Assessing the impacts of such large-scale land-cover change is particularly relevant in this region where (i) water resources are scarce and uneven, and rely on runoff generated in mountain areas (López-Moreno *et al*., 2008), and (ii) the resulting expansion of vegetation has been associated with a decline of streamflow (e.g. Beguería *et al*., 2003; Delgado *et al*., 2010). However, the relationship between changes in vegetation cover and streamflow is still poorly understood (Cosandey *et al*., 2005), primarily because of the complexity of runoff generation processes under Mediterranean conditions (Latron *et al*., 2009).

Studies at the small-catchment scale allow taking a closer look at the hydrological functioning of catchments with different land covers, and hence are useful for understanding the nature and magnitude of the hydrological changes. With this purpose, at the end of the 1990s, the Department of Geo-environmental Processes and Global Change (Instituto Pirenaico de Ecología, CSIC, Spain) monitored two neighbouring catchments in the central Spanish Pyrenees. Both catchments have similar climatic conditions, lithology and topography (Lana-Renault *et al*., 2011), but different land cover: Arnás (2.84 km^2) is an abandoned agricultural catchment subjected to plant colonization; San Salvador (0.92 km^2) is a catchment covered by dense natural forest, representative of undisturbed environments. The aim of this study was to show the seasonal differences between the hydrological responses of those two catchments and relate these differences to differences in land use.

THE CATCHMENTS

The two catchments are located in the upper Aragón River valley, in the central Spanish Pyrenees (Fig. 1), between 850 and 1350 m a.s.l. Bedrock is Eocene flysch composed of thin, alternating layers of sandstones and marls. The mean annual temperature is 10°C, and the mean annual precipitation from 1999 to 2008 was 930 ± 180 mm. Snowfall occurs only occasionally. Mean annual reference evapotranspiration in the study area calculated by the method of Hargreaves–Samani (1985) was 1088 ± 31 mm.

The Arnás catchment was heavily cultivated with cereal crops in non-terraced fields until the 1950s, after which it was abandoned and recolonized by native vegetation. At present 70% of the catchment is occupied by shrubs (*Genista scorpius*, *Echinospartum horridum*, *Buxus sempervirens*), 20% by forest (*Pinus sylvestris*, *Quercus faginea*), and 8% by herbaceous vegetation, indicating more recent farmland abandonment. Bare ground comprises 2% of the catchment. San Salvador is almost totally covered by dense natural forest (98%) of Scots pine (*Pinus sylvestris*), in combination with beech trees (*Fagus sylvatica*) in the shady concavities and oaks (*Quercus faginea*) in areas with a sunny aspect.

In the Arnás catchment, the steep south facing slope (0.50 m m^{-1}) is characterized in the upper parts by relatively active debris flows, which are disconnected from the drainage network. Soils are dominated by compact and shallow calcaric regosols (FAO, 1988), inherited from past human activities. They are generally <0.25 m thick, and show signs of major degradation (Navas *et al.*, 2005). The north facing slope (0.28 m m^{-1}) is marked by an undulating topography with old scars and stable deep mass movement deposits. Brown and deeper haplic kastanozems and haplic phaeozems (up to 0.75 m thick) dominate. In the forested San Salvador catchment a deep, stony colluvium covers most of the slopes (0.52 m m^{-1}), explaining the lack of geomorphological contrasts. Soils are mainly composed of well-developed kastanozems and cambisols, generally between 0.9 and 1.2 m thick, slightly shallower in the upper parts (<0.5 m) (Serrano-Muela, 2005).

Both catchments are equipped with several tipping-bucket rain recorders, a complete weather station, and a gauging station continuously measuring discharge. In the Arnás basin, seven recording piezometers were installed at various distances from the main channel, in areas where significant saturation dynamics have been observed. Two piezometers were installed in the San Salvador basin, and interception was measured in the three different forest covers.

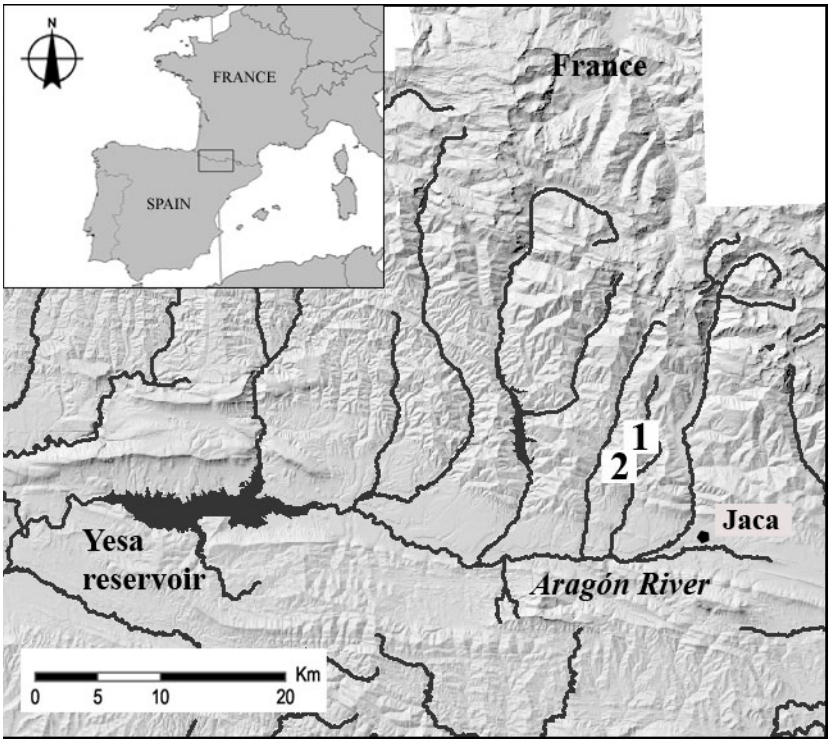

Fig. 1 Location of (1) Arnás (former agricultural catchment), and (2) San Salvador (forested catchment) in the Spanish Pyrenees.

RESULTS AND DISCUSSION

In the study area, as in most of the Mediterranean mountain regions (Latron *et al.*, 2009), the regimes of rainfall and temperature (which has a direct effect on evapotranspiration) is characterized by a marked seasonality. Figure 2 shows that rainfall is concentrated in autumn (September, October, November) and spring (March, April, May); winter (December, January, February) is a period with less precipitation and low evapotranspiration; and summer (June, July, August) is a period with very high evapotranspiration and little rainfall – although intense convective storms of short duration are relatively frequent. The combination of rainfall and evapotranspiration over the water year results in a strong water deficit in the summer and beginning of autumn (dry period), and a wet period in winter and spring.

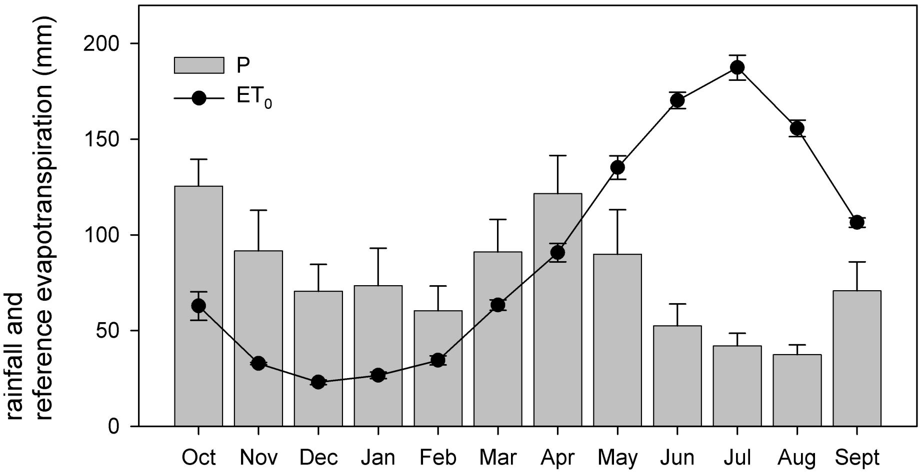

Fig. 2 Monthly mean values of rainfall (P) and reference evapotranspirations (ET_0) over the water year, for the period 1999–2008.

Seasonal differences in runoff

The strong seasonality of the meteorological drivers is the main factor explaining the nonlinearity of the rainfall–runoff relationship over the water year (October–September). Figure 3 shows the average monthly distribution of precipitation and runoff in both the forested and the former agricultural catchments, for the period 1999–2005. For each month, the ratio between the cumulated runoff observed in both catchments is also indicated.

Results evidence the lack of correlation between rainfall and runoff at the monthly scale. This is clearly illustrated during the dry period, especially in September and October, when substantial rainfall events produced little or moderate runoff. As reported in previous studies (e.g. Gallart *et al.*, 2002; Lana-Renault *et al.*, 2007; Latron *et al.*, 2008), in summer and the beginning of autumn the catchment water reserves tend to dry up as a result of less rainfall and high evapotranspirative demand. As a consequence, streamflow response is small because most of the incoming rainfall is used to recharge soil moisture and groundwater. In contrast, March, April and May were the more responsive months, although rainfall was not necessarily the greatest. During wet conditions, catchment water reserves are usually refilled (e.g. Lana-Renault *et al.*, 2007; Latron & Gallart, 2008) and a large part of the rainfall contributes to runoff.

Runoff was higher from June to October in the former agricultural catchment (ratio > 1), with the highest ratios (up to four times higher) at the end of the water year (September) (Fig. 3). Under dry conditions, infiltration excess runoff can occur in response to intense rainstorms in the old agricultural catchment, over bare and poorly vegetated areas close to the main stream (Lana-Renault *et al.*, 2007). In the forested catchment, rainfall interception and tree transpiration accentuate the deficit in the soil water reserves of the forested catchment, which explains an even more limited streamflow response in this catchment. Infiltration excess runoff is negligible, as the bare or poorly vegetated areas comprise less than 1% of the catchment.

In February, April and May runoff was higher in the forested catchment, although the relative differences were not as large as during dry conditions. Under wet conditions, Lana-Renault *et al.* (2007) showed that both saturated excess runoff and subsurface flow were the dominant runoff processes in the former agricultural catchment. In the forested catchment saturated areas were never observed. The slow response and longer recession limbs for most of the hydrographs, together with the strong correlation of the streamflow response and the water table fluctuations (García-Ruiz *et al.*, 2008; Serrano-Muela *et al.*, 2008), indicate a significant contribution of subsurface flow in this catchment. One explanation for the higher runoff observed in the forested catchment under wet conditions could be the existence of a moisture threshold above which the hydrological connectivity within the slopes of the catchment increases abruptly (see e.g. Stieglitz *et al.*, 2003; Medici *et al.*, 2008), such that all or a very large part of the system contributes to runoff.

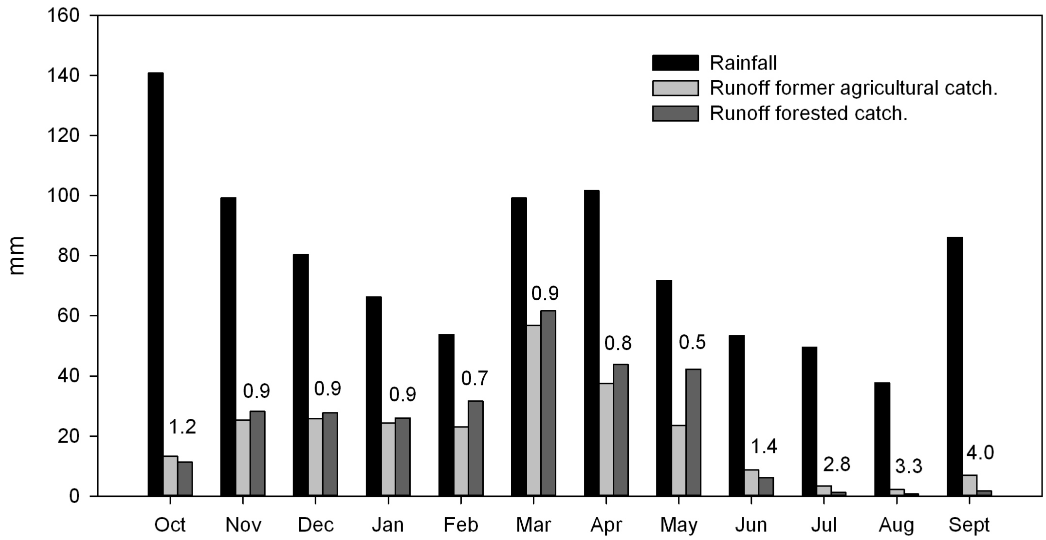

Fig. 3 Average monthly rainfall and runoff in the former agricultural catchment (Arnás) and in the forested catchment (San Salvador) for the period 1999–2005. The ratio $\text{runoff}_{\text{Arnás}}$/ $\text{runoff}_{\text{San Salvador}}$ in each month is indicated.

Differences in hydrographs characteristics

The comparison of a set of flood events caused by the same rainfall event in each catchment demonstrated that peak flow discharge, response time and recession time were statistically different between the catchments (Lana-Renault *et al.*, 2011). In the former agricultural catchment peak flows were always greater (566 *vs* 119 L s^{-1} km^{-2}), the response time was 2- to 3-fold faster (131 *vs* 356 min), and the recession limbs were 1–2 orders of magnitude shorter (7 *vs* 72 h) than in the forested catchment. Differences in storm flow depth were not statistically different and were strongly dependent on catchment moisture conditions: under dry conditions storm flows tended to be greater in the former agricultural catchment, whereas under wet conditions they tended to be greater in the forested one. These differences are clearly illustrated in Fig. 4, which compares three pairs of hydrographs under increasingly wetter conditions. For event 1 (dry conditions), the storm flow depth was 9.7 mm in the former agricultural catchment and only 1.9 mm in the forested one. The difference in storm flow depth decreased as the catchments became wetter, with 18.5 mm and 10.4 mm for event 2, respectively. Under the wettest conditions (event 3), the storm flow depth was greater in the forested catchment (10.2 and 17 mm, respectively).

Peak flows were always higher in the former agricultural catchment although differences tended to decrease from event 1 to event 3 (with 780 *vs* 62 L s^{-1} km^{-2}, 1060 *vs* 178 L s^{-1} km^{-2}, and

855 *vs* 470 L s^{-1} km^{-2}, respectively). Response time was always faster compared to that in the forested catchment (with 165 *vs* 250 min for event 1, 15 *vs* 425 min for event 2, and 5 *vs* 150 min for event 3) and the recession limb always shorter (with 1 *vs* 9h for event 1, 3.5 *vs* 11 h for event 2, and 4 *vs* 8 h for event 3). This series of hydrographs suggests that in the forested catchment, the greater storm flow depths observed under wetter conditions can be explained by the contribution of a slow flow component (i.e. subsurface flow within the soil matrix). At some point (i.e. above a moisture threshold), this contribution may be large enough to explain the greater hydrological response in the forested catchment under wetter conditions.

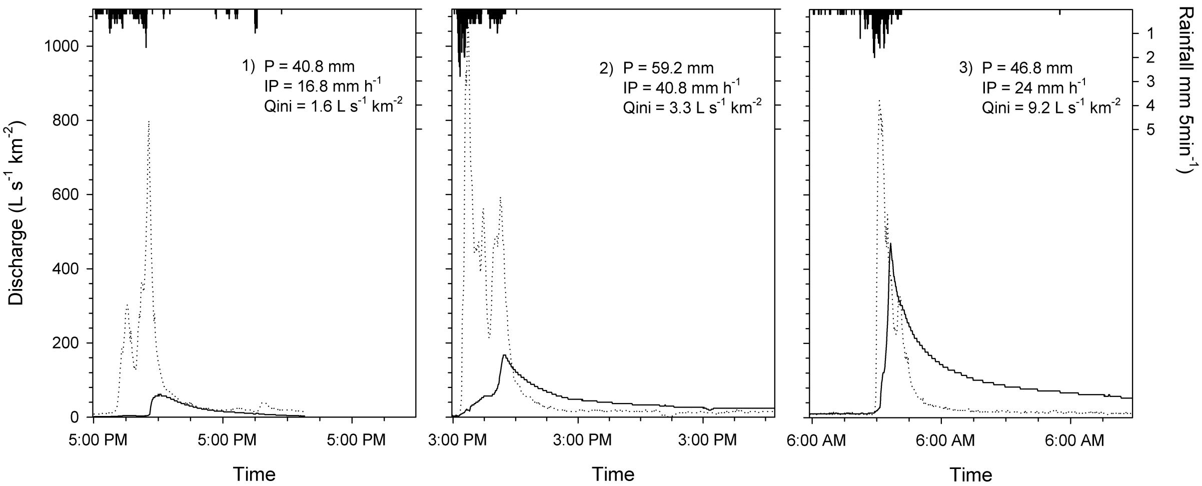

Fig. 4 Hydrographs observed in the former agricultural (dotted line) and forested (solid line) catchments for different preceding conditions. P: rainfall depth; IP: mean rainfall intensity; Qini: baseflow discharge at the start of the event.

The hydrological differences between the two catchments can be related to differences in both vegetation and soil properties (soil depth and permeability), but also to the presence of degraded areas, inherited from past human activities. The thicker soils in the forested catchment favour a greater water storage capacity, but also a greater soil water deficit, which means that more rainfall is needed to refill the water reserves and produce runoff. The greater soil water deficit is accentuated by the presence of trees, which reduce the amount of rainfall reaching the soil (between 22% and 28% of the rainfall, Serrano *et al.*, 2008) and withdraw soil water for transpiration. In the forested catchment, runoff generation is dominated by subsurface flow processes, facilitated by thick and well-developed soils. In the former agricultural catchment, the presence of degraded areas (with less vegetation cover and thin and poorly structured soils), associated with previous agricultural practices, facilitates the occurrence of surface overland flow process (excess infiltration, saturation excess runoff).

CONCLUSIONS

Differences in runoff between a forested and a former agricultural catchment were characterized by a marked seasonality, which in turn was influenced by the regime of the rainfall and temperature over the water year. During summer dry conditions (high temperatures and little rainfall), runoff was limited or moderate in both catchments; however, it was always greater in the former agricultural catchment. Wet conditions during spring and winter (low temperatures and high rainfalls) favoured higher runoff; however we observed that at the end of the wet season runoff tended to be greater in the forested catchment. One explanation for this switching behaviour could be the existence of a moisture threshold above which the hydrological connectivity within the forested catchment (e.g. between ridge and valley) increases rapidly, such that all or a very large part of the system contributes to runoff. The seasonal differences in the hydrological response between the two catchments were also dictated by their contrasting dominant runoff generation processes, which in turn can be related to differences in land use (vegetation and soil properties). In the former agricultural catchment, the complexity of the landscape, inherited from previous human practices, explains that runoff could be generated during wet and dry conditions, through both surface (i.e. infiltration excess and saturation excess overland flow) and subsurface flow. A greater contribution of surface overland flow may explain the greater peak flows, and the shorter response times and recession limbs observed in its hydrographs. In the forested catchment, thicker and well-developed soils favour subsurface flow processes, explaining the lower peakflows and the longer response times and recession limbs observed in its hydrographs.

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REFERENCES

Beguería, S., López-Moreno, J. I., Lorente, A., Seeger, M. & Garcia-Ruiz, J. M. (2003) Assessing the effect of climate oscillations and land-use changes on streamflow in the Central Spanish Pyrenees. *Ambio* 32(4), 283–286.

Cosandey, C., Andréassian, V., Martin, C., Didon-Lescot, J. F., Lavabre, J., Folton, N., Mathys, N. & Richard, D. (2005) The hydrological impact of the mediterranean forest: a review of French research. *J. Hydrol.* 301, 235–249.

Delgado, J., Llorens, P., Nord, G., Calder, I. R. & Gallart, G. (2010) Modelling the hydrological response of a Mediterranean medium-sized headwater basin subject to land cover change: The Cardener River basin (NE Spain). *J. Hydrol.* 383, 125–134.

FAO (1988) Soil Map of the World, revised legend. *World Soil Resources Report 60*, FAO, Rome, Italy.

Gallart, F., Llorens, P., Latron, J. & Regüés, D. (2002) Hydrological processes and their seasonal controls in a small Mediterranean mountain catchment in the Pyrenees. *Hydrol. Earth. System. Sci.* 6(3), 527–537.

García-Ruiz, J. M. & Lana-Renault, N. (2011) Hydrological and erosive consequences of farmland abandonment in Europe, with special reference to the Mediterranean region – a review. *Agr. Ecosyst. Environ.* 140, 317–338.

García-Ruiz, J. M., Regüés, D., Alvera, B., Lana-Renault, N., Serrano-Muela, P., Nadal- Romero, E., Navas, A., Latron, J., Martí-Bono, C. & Arnáez, J. (2008) Flood generation and sediment transport in experimental catchments affected by land use changes in the Central Pyrenees. *J. Hydrol.* 356, 245–260.

Hargreaves, G. H. & Samani, Z. A. (1985) Reference crop evapotranspiration from temperature. *Appl. Eng. Agric.* 1(2), 96–99.

Lana-Renault, N., Latron, J. & Regüés, D. (2007) Streamflow response and water-table dynamics in a sub-Mediterranean research catchment in the Central Spanish Pyrenees. *J. Hydrol.* 347, 497–507.

Lana-Renault, N., Latron, J., Karssenberg, D., Serrano, P., Regüés, D. & Bierkens, M. F. P. (2011) Differences in streamflow in relation to changes in land cover: a comparative study in two sub-Mediterranean mountain catchments. *J. Hydrol.* 411, 366–378.

Latron, J. & Gallart, G. (2008) Runoff generation processes in a small Mediterranean research catchment (Vallcebre, Eastern Pyrenees). *J. Hydrol.* 358, 206–220.

Latron, J., Soler, M., Llorens, P. & Gallart, F. (2008) Spatial and temporal variability of the hydrological response in a small Mediterranean research catchment (Vallcebre, Eastern Pyrenees). *Hydrol. Processes* 22, 775–787.

Latron, J., Llorens, P. & Gallart., F. (2009) The hydrology of Mediterranean mountain areas. *Geogr. Compass* 3/6, 2045–2064.

López-Moreno, J. I., Beniston, M. & García-Ruiz, J. M. (2008) Environmental change and water management in the Pyrenees: Facts and future perspectives for Mediterranean mountains. *Global Planet. Change* 61, 300–312.

Medici, C., Butturini, A., Bernal, S., Vázquez, E., Sabater, F., Vélez, J. I. & Francés, F. (2008) Modelling the non-linear hydrological behaviour of a small Mediterranean forested catchment. *Hydrol. Processes* 22(8), 3814–3828.

Navas, A., Machín, J. & Soto, J. (2005) Assessing soil erosion in a Pyrenean mountain catchment using GIS and fallout ^{137}Cs, *Agr. Ecosyst. Environ.* 105(3), 493–506.

Serrano-Muela, P. (2005) Caracterización de los suelos en una cuenca forestal pirenaica. El ejemplo de San Salvador, valle de Aísa. Memoria del Diploma de Estudios Avanzados, Zaragoza University, Zaragoza.

Serrano-Muela, P., Lana-Renault, N., Nadal-Romero, E., Regüés, D., Latron, J., Martí-Bono, C. & García-Ruíz, J. M. (2008) Forests and their hydrological effect in Mediterranean mountains: The case of the Central Spanish Pyrenees. *Mt. Res. Dev.* 28 (3), 279–285.

Stieglitz, M., Shaman, J., McNamara, J., Kling, G.W., Engel, V. & Shanley, J. (2003) An approach to understanding hydrologic connectivity on the hillslope and the implications for nutrient transport. *Global Biogeochemical Cycles* 17(4), 1105.