water MDPI

*Supplemental Material*

# Evaluating Water Use for Agricultural Intensification in Southern Amazonia Using the Water Footprint Sustainability Assessment

**Michael J. Lathuillière [1,*], Michael T. Coe [2,3], Andrea Castanho [2], Jordan Graesser [4] and Mark S. Johnson [1,5]**

1 Institute for Resources, Environment and Sustainability, University of British Columbia, Vancouver, BC V6T 1Z4, Canada; mark.johnson@ubc.ca
2 Woods Hole Research Center, Falmouth, MA 02540-1644, USA; mtcoe@whrc.org (M.T.C.); acastanho@whrc.org (A.C.)
3 Instituto de Pesquisa Ambiental da Amazônia, Brasília, DF, 71503-505, Brazil
4 Department of Earth and Environment, Boston University, Boston, MA 02215, USA; graesser@bu.edu
5 Department of Earth, Ocean and Atmospheric Sciences, University of British Columbia, Vancouver, BC V6T 1Z4, Canada
* Correspondence: mlathuilliere@alumni.ubc.ca

## 1. Integrated BIosphere Simulator Model Validation of Discharge

Despite successful validation of the model outputs (discharge, evapotranspiration (ET), total water storage) of the Xingu River Basin as per Panday et al. [1], we validated the IBIS modeled runoff for a small area of the Xingu Basin of Mato Grosso (XBMT) encompassing the Xingu Headwaters. River discharge R(t) for the 2000 and 2005 hydrologic years were obtained following equation (1) in the main document compared to station 18430000 located in Marcelândia (Mato Grosso) (10°46′38″ S, 53°5′44″ W) (Figure 1 in the main document) with data available from 1975 to 2005 [2]. Monthly values of R(2000) ($n$ = 12) and R(2005) ($n$ = 4) compared well to publicly available data (Figure S1) showing a Pearson correlation value of r = 0.83 (compared to 0.89 in the 2000s for the Xingu basin in Panday et al. [1]).

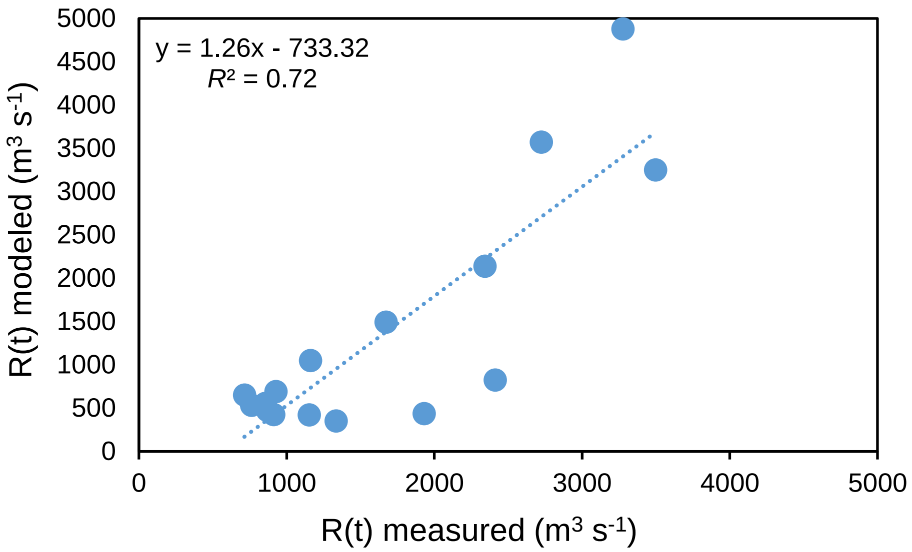


**Figure S1.** Validation of the monthly discharge (R(t)) for the Xingu Headwaters in the 2000 ($n$ = 12) and 2005 ($n$ = 4) hydrologic years at station 18430000 located in Marcelândia (Mato Grosso) [2].

We observed larger discrepancies between modeled and observed R(t) in the November–January period and therefore analyzed inter-annual R(t) using 3-month averages to provide a magnitude of water availability in both dry and wet seasons (Figure S2). The linear regression of modeled versus measured 3-month average discharge for R(2000) ($n$ = 4) gave R(t) modeled = 1.18R(t) measured − 561 ($R^2$ = 0.88)

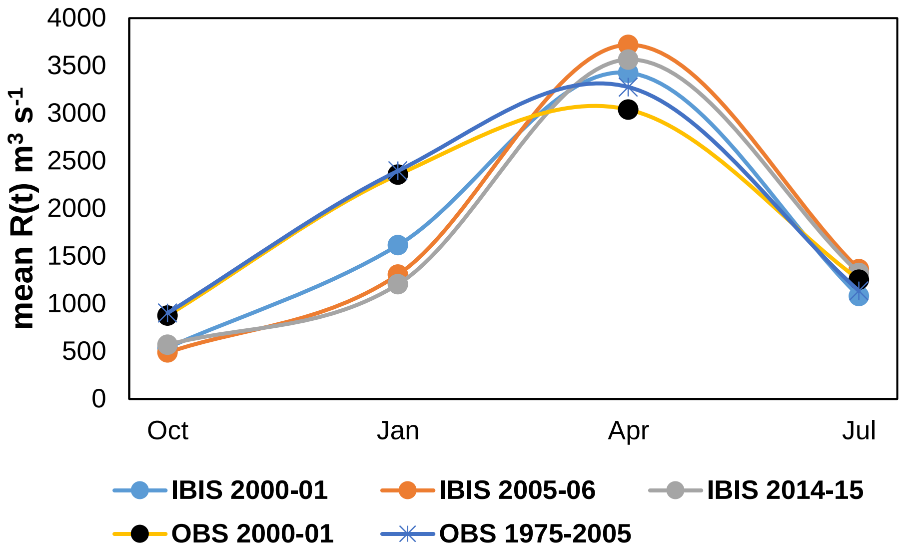


**Figure S2.** Modeled compared to observed 3-month mean discharge at station 18430000 located in Marcelândia (Mato Grosso) [2] for the Xingu Headwaters in the 2000 ($n$ = 12) and 2005 ($n$ = 4) hydrologic years, and for the 1975–2005 ($n$ = 120) period.

## 2. Input Data Used for Water Footprint Accounting

**Table S1.** Cropland and pasture evapotranspiration (ET) according to Lathuillière et al. [3,4] and their respective areas estimated from agricultural production information [5], and Landsat imagery [6] used in the bottom-up approach to determine total ET for agriculture ($ET_{AG}$).

| Land Use | ET | Area [a] 2001, 2015 [5] | Area 2000, 2014 [6] |
|---|---|---|---|
| | mm y$^{-1}$ | Mha | Mha |
| Forest | 1099 | NA | 12.8, 11.4 |
| Pasture | 822–889 | 3.4, 2.3 | 4.4, 4.2 |
| Soybean + fallow | 608–688 | 0.020, 2.2 | |
| Soybean + maize + fallow | 717–808 | 0.095, 0.73 | 0.32, 2.1 |
| Soybean + rice + fallow | | 0.26, 0.081 | |

[a] As data is available by municipalities, these areas represent a percent of total production based on the percent area of the political unit contained with the Xingu Basin of Mato Grosso. Maize and rice are assumed as double crops following soybean planting and are assumed to have similar total crop ET.

**Table S2.** Average livestock population in 2000 and 2014 hydrologic years with livestock water demand and living condition assumptions. Populations were obtained from IBGE [5], include both male and female and were allocated to the Xingu Basin of Mato Grosso based on area of municipalities contained within the basin. Chicken and swine population were recalculated based on life expectancy described in Equation (6).

| Animal | Conditions | Population | | Blue Water Consumption |
|---|---|---|---|---|
| | | Total Live Animals | | $m^3\ d^{-1}$ Animal$^{-1}$ |
| Hydrologic year | | 2000 | 2014 | |
| Cattle | Pasture | 2,534,975 | 3,535,838 | $50 \times 10^{-3}$ |
| Horses [a] | Pasture | 28,954 | 47,766 | $50 \times 10^{-3}$ |
| Buffaloes [a] | Pasture | 4467 | 2781 | $50 \times 10^{-3}$ |
| Donkeys [a,b] | Pasture | 578 | 633 | $50 \times 10^{-3}$ |
| Mules [a,b] | Pasture | 9124 | 12,908 | $50 \times 10^{-3}$ |
| Swine [c] | Confined | 16,358 | 51,724 | $0.125 \times 10^{-3}$ |
| Goats [c] | Pasture | 2388 | 2973 | $4.0 \times 10^{-3}$ |
| Sheep [c] | Pasture | 16,691 | 38,544 | $4.0 \times 10^{-3}$ |
| Chicken/Roosters [c] | Confined | 72,303 | 572,741 | $0.284 \times 10^{-3}$ |

[a] No data available for 2015, the population was assumed constant between 2013 and 2014; [b] [7]; [c] [8].

**Table S3.** Urban, rural, industrial worker population and domestic and industrial water blue water demand in the Xingu Basin of Mato Grosso. Note that blue water consumption was assumed to be 50% of blue water demand. Data derived from IBGE [5] and ANA [7].

| Description | Connected to the Water System? | Population | | Blue Water Demand $m^3\ d^{-1}\ cap^{-1}$ |
|---|---|---|---|---|
| Hydrologic year | | 2000 | 2014 | |
| Total population | | 141,301 | 222,101 | |
| domestic—urban | Yes | 41,806 | 65,711 | $260 \times 10^{-3}$ |
| domestic—urban | No | 47,142 | 74,100 | $70 \times 10^{-3}$ |
| domestic—rural | Yes | 25,653 | 40,322 | $70 \times 10^{-3}$ |
| domestic—rural | No | 26,700 | 41,968 | $70 \times 10^{-3}$ |
| industrial workers | | 88,948 | 139,811 | 3.5 |

## 3. Determination of Environmental Flow Requirements

We followed the procedure described in Smakhtin et al. [9] to derive annual environmental flow requirements (EFR) to maintain ecosystem in "fair" conditions. From an ecological management perspective, these conditions are described as: "the dynamics of the biota have been disturbed. Some sensitive species are lost and/or reduced in extent. Alien species may occur" [9] which is defined from the values of Q50 and Q90 obtained from the long-term discharge data of the Xingu Headwaters observed between 1975 and 2005 at Marcelândia, Mato Grosso (Passagem BR80, station 18430000, 10°46′38″ S, 53°5′44″ W) [2] (Figure S3). Mean annual runoff (MAR) of the Xingu Headwaters was 1921 $m^3\ s^{-1}\ mo^{-1}$ with a Q50 of 1455 $m^3\ s^{-1}\ mo^{-1}$ (76% MAR) and a Q90 of 810 $m^3\ s^{-1}\ mo^{-1}$ (42% MAR). Smakhtin et al. [9] then define EFR as the sum of low flow (Q50) and high flow (Q90) with the low flow set to zero in cases where Q90 exceeds 40% MAR (which is the case for the Xingu Headwaters). Our estimate of annual EFR was therefore 42% MAR which is slightly greater than the Amazon basin average of 31% MAR and the average EFR for the Xingu Basin of 20–25% MAR [9].

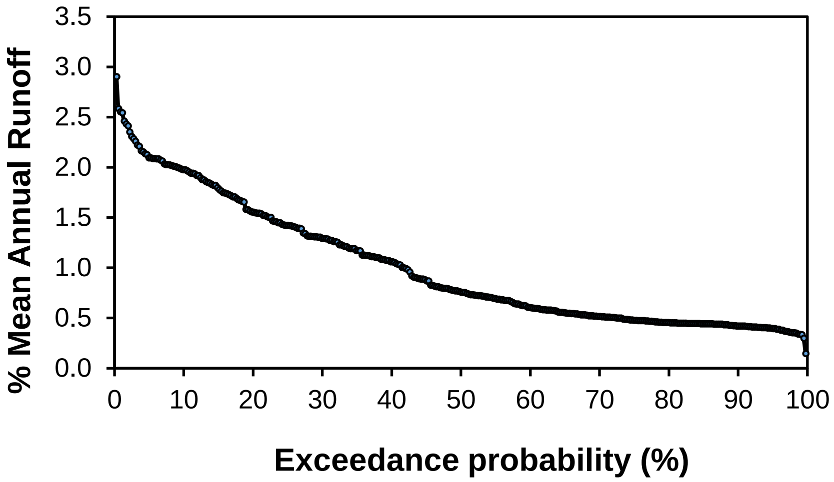


**Figure S3.** Exceedance probability curve for the Xingu Headwaters obtained from monthly observations at Marcelândia, Mato Grosso (Passagem BR80, station 18430000, 10°46′38″ S, 53°5′44″ W) [2] for the 1975–2005 period ($n = 363$).

## 4. Land Use Cover for Deforestation Scenarios

Following deforestation maps obtained from Soares-Filho et al. [10] we extracted forest cover from business-as-usual (BAU) and governance (GOV) scenarios for 2030 and 2050 in the XBMT (Table S4). The deforestation scenario maps were obtained at 1 $km^2$ resolution and estimate a total XBMT surface area of 159,256 $km^2$ [10] compared to 177,000 obtained from Landsat imagery from Graesser and Ramankutty [6].

**Table S4.** Total forest cover as described by land use maps obtained by Soares-Filho et al. [10] in the Xingu Basin of Mato Grosso for business-as-usual (BAU) and governance (GOV) deforestation scenarios.

| Deforestation Scenario | Total Forest Cover ($km^2$) | Total Forest Cover (% basin) |
|---|---|---|
| BAU-2030 | 45,114 | 28.33 |
| BAU-2050 | 32,619 | 20.48 |
| GOV-2030 | 68,462 | 42.99 |
| GOV-2050 | 67,096 | 42.13 |

## 5. Total Blue Water Footprints and Hydrologic Conditions in the Xingu Basin of Mato Grosso

We obtained the total annual blue water consumed in the XBMT according to steps described in Sections 2.3.2 in the main document (Table S5) and compare to the annual estimated runoff in the basin (Table S6) to obtain blue water scarcity for 2000 and 2014, as well as the deforestation and climate scenarios described in Table 1. We also divided annual runoff into 3-month means to account for seasonal variability (Table S6).

**Table S5.** Total blue Water Footprint for agricultural, industrial and domestic uses in the Xingu Basin of Mato Grosso in 2000 and 2014 hydrologic years, as well as scenarios for 2030 and 2050 (see Tables S2 and S3 for input data and Table 1 for the description of scenarios).

| Year | Scenario | Agricultural | Industrial | Domestic |
|---|---|---|---|---|
| | | $km^3\ y^{-1}$ | $km^3\ y^{-1}$ | $km^3\ y^{-1}$ |
| **2000–01** | | 0.153 | $1.60 \times 10^{-5}$ | $4.09 \times 10^{-3}$ |
| **2014–15** | | 0.218 | $2.56 \times 10^{-5}$ | $6.54 \times 10^{-3}$ |
| **2030–31** | $BAU_{RCP4.5}$ | 0.255 | $3.86 \times 10^{-5}$ | $9.86 \times 10^{-3}$ |
| | $BAU_{RCP8.5}$ | 0.255 | $3.86 \times 10^{-5}$ | $9.86 \times 10^{-3}$ |
| | $GOV_{RCP4.5}$ | 0.255 | $3.86 \times 10^{-5}$ | $9.86 \times 10^{-3}$ |
| | $GOV_{RCP8.5}$ | 0.255 | $3.86 \times 10^{-5}$ | $9.86 \times 10^{-3}$ |
| **2050–51** | $BAU_{RCP4.5}$ | 0.517 | $6.53 \times 10^{-5}$ | $1.67 \times 10^{-2}$ |
| | $BAU_{RCP8.5}$ | 0.517 | $6.53 \times 10^{-5}$ | $1.67 \times 10^{-2}$ |
| | $GOV_{RCP4.5}$ | 0.391 | $6.53 \times 10^{-5}$ | $1.67 \times 10^{-2}$ |
| | $GOV_{RCP8.5}$ | 3.81 | $6.53 \times 10^{-5}$ | $1.67 \times 10^{-2}$ |

**Table S6.** Total annual and 3-month mean runoff in the Xingu Basin of Mato Grosso obtained from IBIS simulations and land use (Equation (1) in the main document). Values in brackets are the percent changes compared to the 2000–2001 hydrologic year.

| | | | | Runoff | | | | |
|---|---|---|---|---|---|---|---|---|
| **Year** | **Scenario** | **Precipitation** | **PNV [a]** | **Annual** | **Sep-Nov** | **Dec-Feb** | **Mar-May** | **Jun-Aug** |
| | | $mm\ y^{-1}$ | $km^3\ y^{-1}$ | | $km^3$ 3-months$^{-1}$ | | | |
| **2000–01** | | 1999 | 69.8 | 74.9 | 5.8 | 20.7 | 36.9 | 11.5 |
| **2014–15** | | 1934 | 64.1 | 70.4 | 5.9 | 14.3 | 38.3 | 12.0 |
| **2030–31** | $BAU_{RCP4.5}$ | 1966 | 67.9 | 78.6 (+5) | 6.9 (+20) | 7.1 (−66) | 47.1 (+28) | 17.4 (+52) |
| | $BAU_{RCP8.5}$ | 1971 | 69.1 | 80.0 (+7) | 6.6 (+14) | 6.1 (−69) | 49.5 (+34) | 17.5 (+52) |
| | $GOV_{RCP4.5}$ | 1966 | 67.9 | 76.3 (+2) | 6.9 (+19) | 6.6 (−68) | 45.6 (+24) | 17.3 (+50) |
| | $GOV_{RCP8.5}$ | 1971 | 69.1 | 77.8 (+4) | 6.5 (+13) | 6.0 (−71) | 47.9 (+30) | 17.4 (+51) |
| **2050–51** | $BAU_{RCP4.5}$ | 1969 | 69.0 | 80.8 (+8) | 6.9 (+19) | 8.0 (−62) | 49.1 (+33) | 16.9 (+47) |
| | $BAU_{RCP8.5}$ | 1952 | 65.7 | 77.7 (+4) | 6.8 (+18) | 6.3 (−69) | 47.6 (+29) | 17.0 (+48) |
| | $GOV_{RCP4.5}$ | 1969 | 69.0 | 77.4 (+3) | 6.8 (+18) | 7.2 (−65) | 46.8 (+27) | 16.6 (+45) |
| | $GOV_{RCP8.5}$ | 1952 | 65.7 | 74.3 (−1) | 6.8 (+17) | 5.9 (−71) | 44.9 (+22) | 16.7 (+45) |

[a] Potential Natural Vegetation following Ramankutty and Foley [11].

## 6. Land Use Evapotranspiration Contributions through Top-Down and Bottom-Up Approaches

We used both top-down and bottom-up approaches to estimate changes in land contributions to ET. First, the bottom-up approach was used following steps described in the main document in order to devise changes between 2000 and 2014. Results were compared to land ET estimates derived by Silvério et al. [12] using MODerate resolution Imaging Spectroradiometer ET product [13] in the XBMT (Table S7). Our results were close than those of Silvério et al. [12] who report a decrease in ET of approximately 35 $km^3$ in the 2000s (considering land use transitions affecting natural vegetation). Silvério et al. [12] report that 12% of forests in the basin (18,838 $km^2$) were either converted to cropland (3347 $km^2$) or pasture (15,491 $km^2$) between 2000 and 2010. The difference between our values obtained through the bottom-up approach and those of Silverio et al. [12] was attributed to differences in resolution between the products used (1 km for MODIS compared to 30 m for Landsat) as well as the model steps used to obtain ET with the Penman-Monteith equation in MOD16 [13] and our procedure (see Section 2.3.2 in the main document).

**Table S7.** Individual land use contributions to evapotranspiration (ET) obtained in this study using the bottom-up approach between 2000 and 2010 compared to values obtained by Silvério et al. [12] using the MODIS ET product [13].

| Land Use | Study | 2000 | 2005 | 2010 | 2014 |
|---|---|---|---|---|---|
| | | km³ y⁻¹ | | | |
| Forest, shrubland | This study | 141 | 129 | | 125 |
| Forest, Cerrado | Silvério et al. [12] | 142 | 142 | 138 | |
| Pasture | This study | 37.8 | 41.2 | | 35.6 |
| | Silvério et al. [12] | 34.7 | 47.7 | 50.7 | |
| Cropland | This study | 2.8 | 10.2 | | 14.3 |
| | Silvério et al. [12] | 1.6 | 6.2 | 8.9 | |
| Agriculture (Pasture + Cropland) | This study | 40.6 | 51.5 | | 49.9 |
| | Silvério et al. [12] | 36.3 | 53.9 | 59.6 | |
| Total ET (Forest + Agriculture) | This study | 181 | 180 | | 175 |
| | Silvério et al. [12] | 179 | 195 | 198 | |
| Deviations in total ET (Forest + Agriculture) | Comparison between this study and Silvério et al. [12] | +1% | −8% | | |

We then used the top-down approach using IBIS simulations to describe changes in ET land contributions following deforestation and climate change scenarios (Table S8, Figure S4).

**Table S8.** Values of total evapotranspiration ($ET_T$), evapotranspiration of the natural vegetation ($ET_{NV}$), potential natural vegetation ($ET_{PNV}$), and the combined ET of agriculture and residual landscapes ($ET_{AG}$ + $ET_R$) in the Xingu Basin of Mato Grosso between 2000 and 2050 hydrologic years considering business-as-usual (BAU) and governance (GOV) deforestation, and Representative Concentration Pathways (RCP 4.5 and 8.5 W m$^{-2}$). All values were obtained using the top-down approach. Values are plotted in Figure S4.

| Year | Scenario | $ET_T$ | $ET_{NV}$ | $ET_{PNV}$ | $ET_{AG}$ + $ET_R$ |
|---|---|---|---|---|---|
| | | | | km³ y⁻¹ | |
| **2000–01** | | 279.0 | 191.2 | 284.1 | 87.8 |
| **2014–15** | | 272.0 | 172.2 | 278.4 | 99.8 |
| **2030–31** | $BAU_{RCP4.5}$ | 269.6 | 82.1 | 280.3 | 187.5 |
| | $BAU_{RCP8.5}$ | 271.8 | 82.0 | 279.7 | 189.8 |
| | $GOV_{RCP4.5}$ | 268.9 | 122.9 | 280.3 | 146.0 |
| | $GOV_{RCP8.5}$ | 271.1 | 122.7 | 279.7 | 148.4 |
| **2050–51** | $BAU_{RCP4.5}$ | 267.9 | 60.0 | 279.9 | 207.9 |
| | $BAU_{RCP8.5}$ | 271.3 | 60.0 | 280.0 | 211.3 |
| | $GOV_{RCP4.5}$ | 268.0 | 122.5 | 279.9 | 145.5 |
| | $GOV_{RCP8.5}$ | 271.4 | 122.3 | 280.0 | 149.1 |

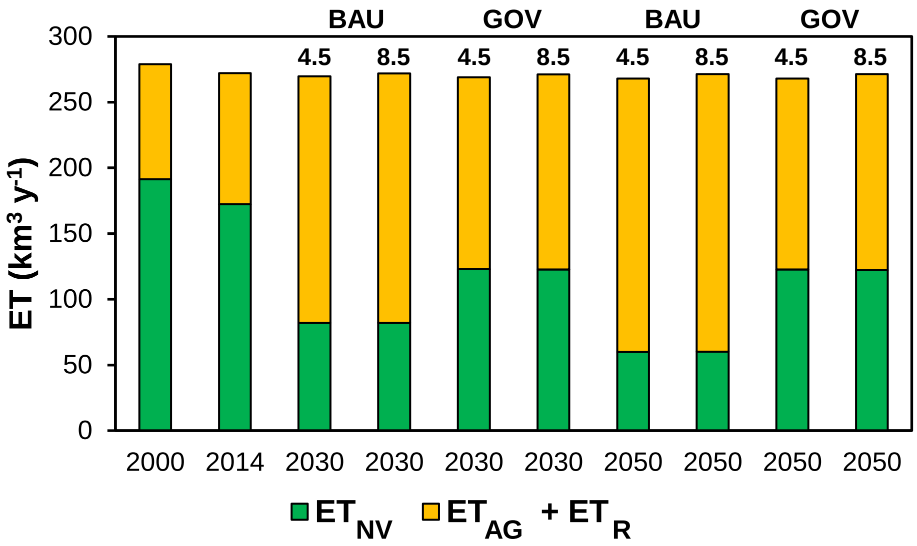


**Figure S4.** Land contributions to evapotranspiration (ET) from natural vegetation ($ET_{NV}$), agricultural land ($ET_{AG}$) and residual landscapes ($ET_R$) in the Xingu Basin of Mato Grosso between 2000 and 2050 using the top-down approach and following business-as-usual (BAU) and governance (GOV) deforestation, and climate change scenarios (Representative Concentration Pathway 4.5 and 8.5 W m$^{-2}$) as described in Table 1.

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