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Pathways towards NetZero emissions in grain cropping farms

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Abstract: Markets and society increasingly demand food production systems that balance output, profitability, and environmental impact. Here we quantify the likely efficacy of alternative farming strategies in terms of their ability to mitigate greenhouse gas (GHG) emissions, enhance farmer profitability, and mitigate downside risks. We used the APSFarm NextGen model, to simulate crop production and emissions of six contrasting farming strategies: (i) intensive energy use (Fuel Burner), (ii) Opportunistic crop rotations, (iii) Rigid crop rotations, (iv) Agroecology, (v) Conservation Agriculture, and (vi) NetZero. We simulated 50 years of climatology (1970-2019) and a range of future climate scenarios (2021-2070), across three case study farms of Queensland. Benefits and trade-offs associated to each strategy are discussed in terms of gross margins (GM, AU\$ ha^{-1} $year^{-1}$), downside risks (likelihood of a negative return), and GHG emissions (kg CO_2-eq ha^{-1} yr^{-1}). This study highlights the potential for achieving NetZero emissions in Queensland's agricultural sector, providing guidance for farmers and policymakers to develop adaptive strategies that align with government goals. Additionally, the whole farm modelling framework for NetZero research used in this study is also applicable to agricultural emission reduction plans in other countries and regions across the world.

Keywords: *Farm profits and risks; Greenhouse gas emissions; Whole farm modelling; APSFarm; APSIM*

1. INTRODUCTION

Achieving NetZero without affecting productivity, farm profits, or risk exposure, represents a challenge for agriculture anywhere in the world. The Australian government aims for a 43% reduction in emissions by 2030 and net zero by 2050, in alignment with the Paris Agreement (2015). In Australia, agriculture accounts for 14% of total GHG emissions (Verge, et al 2007). Numerous studies demonstrate that agricultural management strategies—including strategic crop rotation, organic fertilizers and pesticides, nitrogen-fixing and cover crops, no-till farming, and legume cultivation—significantly reduce emissions in agricultural systems (Donner and Kucharik, 2003; Halvorson et al. 2010; Halvorson et al. 2008; Jiang et al. 2018; Muhammad et al. 2019; Parkin and Kaspar, 2006). However, there are natural limitations in reducing GHG emissions from agricultural system due to the cycling of soil organic carbon and soil organic nitrogen (Chen et al. 2010; Luo et al. 2011). Achieving NetZero emissions in agriculture only be feasible through compensatory measures such as carbon sequestration (González-Ramírez et al. 2012).

Functional crop simulation models such as APSIM (Holzworth et al., 2014) be used to quantify whole-farm GHG emissions to inform on the likely benefits and trade-offs of alternative pathways toward NetZero. APSIM's whole-farm model APSFarm (Rodriguez et al., 2014), was originally designed and validated to quantify the effects of alternative farm business designs on production, economic and environmental indicators. APSFarm allows users a high degree of flexibility to design and test alternative practices, enterprises, and farm configurations. Model outputs can then be used to inform discussions with practitioners on the allocation of resources that maximize farmers' objectives and manage trade-offs between production, economic and environmental indicators (Gil et al. 2018; Kyle et al. 2023).

The aim of this in-silico study was to (i) incorporate GHG emission capabilities in APSFarm NextGen, to simulate emissions and return from cropping systems, (ii) calculate benefits and trade-offs across economic and environmental indicators for alternative pathways towards achieving NetZero, and (iii) assess the area of afforestation needed to offset GHG emissions to reach NetZero.

2. METHODS

2.1. Climate and Soil Data Collection

Previously published case study farms from each of three regions, Georgetown (142.85°E, 18.15°S) in Queensland's semi-arid tropics, Capella (148.02°E, 23.09°S) in Central Queensland, and Dalby (151.27°E, 27.17°S) in the Darling Downs, of Australia, were selected for this study (Adhikari et al. 2023; Rodriguez et al. 2014; Rodriguez et al. 2011). Historical climate data (1970-2019) was downloaded from the Scientific Information for Landowners (Jeffrey et al. 2001). For every case study farm, the corresponding soil data were obtained from the APSoil database (Dalgliesh et al. 2012).

2.2. Simulated strategies

To compare the potential for zero emissions of different agricultural management strategies, six farm strategies were parameterized based on the case study farms.

(i) High energy use or fuel burner (FB): This strategy focuses on yield optimization through a rigid crop rotation system and the heavy use of chemical fertilizers. In FB strategy, tillage is commonly performed post-harvest to incorporate crop residues into the soil. Chemical pesticides and herbicides are utilized to control pests and weeds. This approach aims to achieve high yields through substantial inputs and may exert considerable stress on the soil and the environment. The main crops include wheat, sorghum, and chickpea.

(ii) Opportunistic crop rotation (OR): refers to a flexible management strategy, whereby farmers adjust the types of crops and planting schedules based on indicators such as soil moisture, rainfall, and planting area. This strategy employs chemical fertilizers, pesticides, and herbicides, plus no-till after harvest. The crops planted include sorghum, wheat, and chickpea (Rodriguez et al. 2011). This strategy is one of the baseline strategies.

(iii) Rigid crop rotation (RR): refers to a more fixed management strategy, with farmers adhering to a pre-established planting plan, planting specific crops at fixed times regardless of other conditions. The strategy uses no-till after harvesting the crops. The crops planted include sorghum, wheat, maize, and chickpea (Rodriguez et al. 2011). This strategy is one of the baseline strategies.

(iv) Agroecology (AE): This strategy emphasizes the integration of ecological principles into agricultural management to support sustainable agriculture. In terms of crop nutrition management, AE uses organic manure instead of chemical fertilizer, likewise, pest and weed control is done using organic herbicides and natural pesticides, focusing on ecological balance and environmental protection. The variety of crops includes sorghum, wheat, maize, mungbean, soybean, and chickpea. This approach aims to achieve sustainable agricultural development while protecting the ecosystem (Gliessman S 2018).

(v) Conservation agriculture (CA): focuses on enhancing production efficiency while protecting soil health. This strategy employs opportunistic crop rotation and no-till management aimed at improving resilience, reducing soil erosion, and improving soil health. The CA strategy uses chemical pesticides and herbicides for pest and weed control, as well as chemical fertilizers for crop nutrition management. The primary crops grown include sorghum, wheat, maize, mungbean, soybean, and chickpea. By minimizing soil disturbance and maintaining soil cover, CA strives to enhance soil health without decreasing yield (Pittelkow et al. 2015).

(vi) NetZero (NZ): The management of this strategy is the same as that of AE. However, afforestation is used to offset farm residue greenhouse gas emissions by incrementally increasing the afforested area on the farm. Specific percentages of farm area (2%, 4%, 6%, 8%, 10% until achieving zero emissions) are designated for afforestation to systematically evaluate the impact on achieving NetZero objectives.

2.3. Greenhouse gas emissions, gross margins, and downside risk

The APSFarm Next Gen model was used to estimate whole-farm GHG emissions. Following the GHG Protocol scoping framework, our analysis primarily focuses on Scope 1 (direct emissions within the farm gate boundary), Scope 2 (indirect emissions from fuel manufacturing) and part of Scope 3 (indirect upstream emissions from agrochemical manufacturing). We estimated GHG emissions in CO_2 equivalents from the following sources: 1. Soil CO_2 and N_2O fluxes: GHG emissions directly resulting from soil processes under various farm management strategies, were estimated using default APSIM models (Probert et al. 1998; Thorburn et al, 2010); 2. Fuel emissions: fuel burning and manufacturing for farm machinery and equipment (Kim & Dale 2003); 3. Emissions from agrochemical processing and applications: chemical pesticides and herbicides.

Emissions associated with livestock rearing for manure production were allocated to the livestock sector in accordance with system boundaries rules. Methane emissions were excluded from the analysis, as the simulated dryland cropping systems do not involve significant CH_4 sources. System boundaries followed the cradle-to-farm-gate approach as defined by the GHG Protocol Corporate Standard. While we included Scope 3 (input manufacturing) emissions where reliable emission factors were available, certain upstream emissions (organic pesticide and herbicide production) were excluded due to a lack of region-specific lifecycle inventory data. This partial inclusion reflects practical limitations in agricultural GHG accounting. The current model simulates weed control by resetting weed growth parameters upon herbicide application without distinguishing root-kill efficacy, acknowledging that organic herbicides may permit root survival and regrowth, with future iterations aiming to incorporate root persistence parameters. The total GHG emissions (t CO_2 -equivalent) were calculated as follows:

$$GHG_{emission} = N_2O * 298 - \Delta SOC * 3.67 + N_f * 2.68 + N_p * 24.5 + N_h * 22.8 \qquad eq.1$$

Where:

- 298 is the 100-year global warming potential (GWP) for N_2O (Houghton et al. 2001). 100-GWP is an international standard adopted by the Kyoto Protocol, which ensures consistency and comparability across studies and policies. The 100-year time frame allows us to capture both the immediate effects of short-lived pollutants and the long-term effects of cumulative pollutants (Allen et. al 2016).
- ΔSOC (kg) is the change in SOC (0-300 mm) in x (during the simulation periods) years of the simulation and the initial SOC content. The term 3.67 is the conversion factor from C to CO_2 based on their respective molar masses (44 g/mol for CO2 and 12 g/mol for C).
- N_f (kg) is the diesel fuel consumption in x (from 0 to 50) years. The term 2.68 is the global warming impact (GWI, kg CO_2 -equivalent/kg) (Kim & Dale 2003).
- N_p (kg)is the pesticide consumption in x (from 0 to 50) years. For chemical pesticides, the term 24.5 refers to the GWI (kg CO_2 -equivalent/kg) of pesticides (Kim & Dale 2003). For organic pesticides, this item assumes 0.
- N_h (kg) is the herbicide consumption in x (from 0 to 50) years. For chemical pesticides, the term 22.8 refers to the GWI (kg CO_2 -equivalent/kg) of herbicides (Kim & Dale 2003). For organic herbicides, this item assumes 0.

In our study, afforestation was simulated using the Eucalyptus grandis model in APSIM, with a 3x3m square spacing between trees. No additional fertilizers or pesticides were applied. The simulation spanned a 15-year growth period – a duration selected to align with the species' peak biomass accumulation phase (Pérez-Cruzado, Merino & Rodríguez-Soalleiro 2011). After a 15-year growth period, the trees are harvested without tilling the soil and replanted immediately. The CO_2 offset calculation strictly reflects carbon sequestration under cradle-to-farm-gate boundary, i.e., carbon fixed in tree biomass during the growth phase is counted as an offset regardless of post-harvest utilization (e.g., biomass energy). This approach aligns with the study's focus on achieving farm-level net-zero emissions, where temporary carbon storage within the farm boundary is valid for neutralizing on-farm emissions. The CO_2 equivalent of eucalyptus offset was calculated as follows:

$$GHG_{offset} = E_w * 0.48 * 3.67 \qquad eq.\ 2$$

Here:

- E_w (kg) represents the total biomass of the eucalyptus trees, both above and below ground.
- The factor 0.48 corresponds to the carbon fraction (CF) of eucalyptus, indicating that 48% of the eucalyptus biomass is carbon, as identified in the study by Pérez (Pérez-Cruzado, Merino & Rodríguez-Soalleiro 2011).
- The term 3.67 is the conversion factor from carbon to CO_2 based on their respective molar masses (44 g/mol for CO_2 and 12 g/mol for C).

Thus, the net GHG emissions of the whole farm were calculated as:

$$GHG_{net} = GHG_{emission} - GHG_{offset} * \alpha \qquad eq.3$$

Where α is the system boundary adjustment factor (α=1 in this study). This simplification aligns with the study's scope of quantifying on-farm carbon stock changes rather than tracking off-farm biomass utilization. Future implementations of this framework could adjust to broader boundaries.

The APSFarm economic module monitors input costs and sales revenue to compute the gross margin for each crop type. The data on seed costs and agricultural product prices were sourced from AgMargins. To minimize variability, we applied a five-year average. To compare the profitability of different strategies, the GM (AU$) was calculated using the equation:

$$GM = M_C - C_s - C_f - C_m - C_h - C_p - C_d \qquad eq.4$$

Where M_c (margin of all crops) is calculated as the crop price (AU$ t^{-1}) multiplied by crop yield (t). C_s (seed cost), C_f (cost of fertilizer), C_m (cost of manure), C_h (cost of herbicide), C_p (cost of pesticide), and C_d (cost of diesel).

In this study, downside risk (%) is defined as the probability of annual gross margins falling below zero. Using the APSFarm model, we calculated annual Gross Margin for various strategies across different sites. We then computed the cumulative distribution probabilities of annual returns using R (4.3) to determine the downside risk (Ihaka & Gentleman 1996).

3. RESULT

3.1. Trade-offs GHG emissions, gross margin, and downside risk

Annual gross margin (AU$ ha^{-1} yr^{-1}), annual GHG emissions (kg CO_2-eq ha^{-1} yr^{-1}), and downside risk (%) using climatology (1970-2019) for the three case study farms are presented in Figure 1.

At the three sites, the CA strategy always had the highest mean gross margins (Figure 1). The NZ strategy always had the lowest mean GHG emissions. The mean gross margin of NZ strategies (NZ4, NZ6, NZ14) was similar to baseline strategies (opportunistic and rigid). Across all the strategies, only the NZ strategy could achieve NetZero emissions. As shown in Figure 1, NetZero mean emission farms were achieved with NZ14, NZ6, and NZ4 strategies at all three experimental sites. At Georgetown, NZ14 resulted in GHG emissions of -21 kg CO_2-eq ha^{-1} yr^{-1} and a Gross Margin of 608 AU$ ha^{-1} yr^{-1}. At Capella, NZ6 showed GHG emissions of -184 kg CO_2-eq ha^{-1} yr^{-1} and a Gross Margin of 903 AU$ ha^{-1} yr^{-1}. At Dalby, NZ4 produced GHG emissions of -42 kg CO_2-eq ha^{-1} yr^{-1} and a Gross Margin of 1193 AU$ ha^{-1} yr^{-1}. Compared to the baseline strategies, the NZ strategies reduced downside risk. For example, the downside risk of NZ4, OR, and RR strategy at Dalby were 10%, 12%, and 16%, respectively (Figure 1).

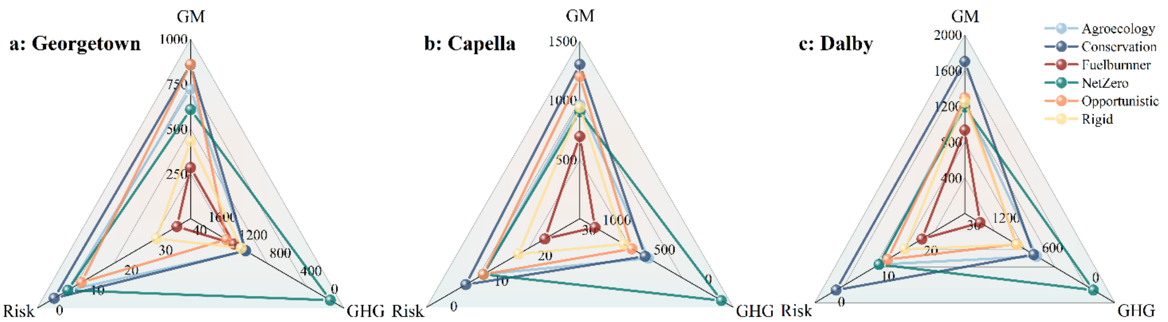

Figure 1 Trade-offs Gross Margin (AU$ ha^{-1} yr^{-1}), GHG (kg CO_2-eq ha^{-1} yr^{-1}), and downside risk (%) under historical climate scenarios (1970-2019) at three experimental sites. Every point summarized the mean value of one strategy for 50 years. In each radar chart, the performance of each strategy is represented by lines connecting the vertices. The NetZero strategy for each site was selected as the minimum afforestation area (Georgetown: 14%, Capella: 6%, Dalby: 4%) that could achieve NetZero mean emission

3.2. Optimizing Farmland Allocation for Afforestation to achieve NetZero farm

NZ series strategy can achieve net zero emissions under historical climate in Dalby, Capella, and Georgetown by dedicating 4%, 6%, and 14%, respectively, of the farm area to afforestation. These results, except for the Georgetown region, were similar to those produced by GRDC (Sevenster et al 2022). GRDC's work showed that 5.5% of the current area used for grain cultivation would need to be set aside for environmental plantings to offset the GHG emissions. A key difference between our result and GRDC's work is that the annual mean temperature in Georgetown is higher (26.68℃) than that in the other regions (19.36℃ and 22.67℃). Compared with the CAstrategy, the NZ series strategies had lower gross margin but equal downside risk (Figure 1).

4. CONCLUSION

Based on our simulation, all the strategies involve trade-offs in three dimensions. Our results showed that using organic fertilizers, no-tillage farming, planting cover crops and legumes, and opportunistic crop rotation could mitigate GHG emissions but not enough to achieve NetZero farm. Therefore, measures to offset farm GHG emissions are necessary. NZ series strategy can achieve net zero emissions under historical climate in Dalby, Capella, and Georgetown by dedicating 4%, 6%, and 14%, respectively, of the farm area to afforestation. Further investigation will assess more how future climate factors influence farms' potential to achieve NetZero emissions. The case study demonstrated the potential of NetZero emissions for QLD agricultural farms, which can guide farmers and policymakers in developing adaptive strategies to achieve the NetZero emissions goals of the QLD government. Additionally, the whole farm modelling framework for NetZero research used in this study is also applicable to agricultural emission reduction plans in other countries and regions across the world.

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REFERENCES

Adhikari L, et al. (2023). A framework for the assessment of farm diversification options in broadacre agriculture. Agricultural Systems, 210, 103724. (Doi: 10.1016/j.agsy.2023.103724)

Allen, M. R., Fuglestvedt, J. S., Shine, K. P., Reisinger, A., Pierrehumbert, R. T., & Forster, P. M. (2016). New use of global warming potentials to compare cumulative and short-lived climate pollutants. Nat. Clim. Change., 6(8), 773-776. (Doi: 10.1038/nclimate2998.)

Chen C, et al. (2010). Quantifying the effects of climate trends in the past 43 years (1961–2003) on crop growth and water demand in the North China Plain. Climatic Change, 100(3-4), 559-578. (Doi: 10.1007/s10584-009-9690-3)

Dalgliesh N et al. (2012). APSoil-providing soils information to consultants, farmers and researchers. 16th Australian Agronomy Conference 2012: Armidale, NSW

Donner S D, and Kucharik C J. (2003). Evaluating the impacts of land management and climate variability on crop production and nitrate export across the Upper Mississippi Basin. Global Biogeochemical Cycles, 17(3). (Doi: 10.1029/2001GB001808)

Gil, J. D., Garrett, R. D., Rotz, A., Daioglou, V., Valentim, J., Pires, G. F., Costa, M. H., Lopes, L., Reis, J. C. (2018). Tradeoffs in the quest for climate smart agricultural intensification in Mato Grosso, Brazil. Environ. Res. Lett., 13(6), 064025. (Doi:10.1088/1748-9326/aac4d1.)

Gliessman S. (2018). Defining agroecology. Agroecology and Sustainable Food Systems, 42(6), 599-600.
(Doi: 10.1080/21683565.2018.1432329)

González-Ramírez et al. (2012). An overview of carbon offsets from agriculture. Annu. Rev. Resour. Econ., 4(1), 145-160. (Doi: 10.1146/annurev-resource-083110-120016)

Halvorson A D, et al. (2010). Tillage and inorganic nitrogen source effects on nitrous oxide emissions from irrigated cropping systems. Soil Science Society of America Journal, 74(2), 436-445. (Doi: 10.2136/sssaj2009.0072)

Halvorson A D et al. (2008). Nitrogen, tillage, and crop rotation effects on nitrous oxide emissions from irrigated cropping systems. Journal of Environmental Quality, 37(4), 1337-1344.
(Doi: 10.2134/jeq2007.0268)

Holzworth, D. P., Huth, N. I., deVoil, P. G., Zurcher, E. J., Herrmann, N. I., McLean, G., ... & Keating, B. A. (2014). APSIM–evolution towards a new generation of agricultural systems simulation. Environ. Model. Softw, 62, 327-350. (Doi: 10.1016/j.envsoft.2014.07.009)

Houghton, J. T., Ding, Y., Griggs, D. J., Noguer, M., van der Linden, P. J., Dai, X., Maskell, K., Johnson, C. A. (2001). Climate change 2001: the scientific basis (Vol. 881, No. 9). Cambridge: Cambridge university press.

Ihaka, R., & Gentleman, R. (1996). R: a language for data analysis and graphics. Journal of computational and graphical statistics, 5(3), 299-314. (Doi:10.1080/10618600.1996.10474713)

Jeffrey S J et al. (2001). Using spatial interpolation to construct a comprehensive archive of Australian climate data. Environmental Modelling & Software, 16(4), 309-330. (Doi: 10.1016/S1364-8152(01)00008-1)
Jiang G, et al. (2018). Manure and mineral fertiliser effects on crop yield and soil carbon sequestration: a meta‐analysis and modelling across China. Global Biogeochemical Cycles, 32(11), 1659-1672. (Doi: 10.1029/2018GB005960)
Kim, S., Dale, B. E. (2003). Cumulative energy and global warming impact from the production of biomass for biobased products. J. Ind. Ecol., 7(3‐4), 147-162. (Doi: 10.1162/108819803323059442.)
Kyle, P., Ollenburger, M., Zhang, X., Niazi, H., Durga, S., Ou, Y. (2023). Assessing Multi‐Dimensional Impacts of Achieving Sustainability Goals by Projecting the Sustainable Agriculture Matrix Into the Future. Earth's Future, 11(10), e2022EF003323. (Doi:10.1029/2022EF003323.)
Luo Z, et al. (2011). Modelling long-term soil carbon dynamics and sequestration potential in semi-arid agro-ecosystems. Agricultural and Forest Meteorology, 151(12), 1529-1544. (Doi: 10.1016/ j.agrformet. 2011. 06. 011)
Muhammad I, et al. (2019). Regulation of soil CO2 and N2O emissions by cover crops: A meta-analysis. Soil and Tillage Research, 192, 103-112. (Doi: 10.1016/j.still.2019.04.020)
Paris agreement. report of the conference of the parties to the United Nations framework convention on climate change (21st session, 2015: Paris). Retrieved December. Vol. 4. No. 2017. Getzville, NY, USA: HeinOnline. (https://heinonline.org/)
Parkin T B, and Kaspar T C. (2006). Nitrous oxide emissions from corn–soybean systems in the Midwest. Journal of Environmental Quality, 35(4), 1496-1506. (Doi: 10.2134/jeq2005.0183)
Pérez-Cruzado, C., Merino, A.,Rodríguez-Soalleiro, R. (2011). A management tool for estimating bioenergy production and carbon sequestration in Eucalyptus globulus and Eucalyptus nitens grown as short rotation woody crops in north-west Spain. Biomass Bioenergy, 35(7), 2839-2851. (Doi: 10.1016/j.biombioe.2011.03.020)
Pittelkow, et al. Productivity limits and potentials of the principles of conservation agriculture. Nature 517.7534 (2015): 365-368. (Doi: 10.1038/nature13809)
Probert, M. E., Dimes, J. P., Keating, B. A., Dalal, R. C., & Strong, W. M. (1998). APSIM's water and nitrogen modules and simulation of the dynamics of water and nitrogen in fallow systems. Agr. Sys., 56(1), 1-28. (DOI: 10.1016/S0308-521X(97)00028-0.)
Rodriguez D, et al. (2011). The intrinsic plasticity of farm businesses and their resilience to change. An Australian example. Field Crops Research, 124(2), 157-170. (Doi: 10.1016/j.fcr.2011.02.012)
Rodriguez, D., Cox, H., deVoil, P., Power, B. (2014). A participatory whole farm modelling approach to understand impacts and increase preparedness to climate change in Australia. Agric. Syst., 126, 50-61. (Doi: 10.1016/j.agsy.2013.04.003.)
Sevenster M et al. (2022). Australian grains baseline and mitigation assessment. GRAINS RESEARCH UPDATE, 16. (https://grdc.com.au/)
Thorburn, P. J., Biggs, J. S., Collins, K., & Probert, M. E. (2010). Using the APSIM model to estimate nitrous oxide emissions from diverse Australian sugarcane production systems. *Agriculture, Ecosystems & Environment*, *136*(3-4), 343-350.(Doi:10.1016/j.agee.2009.12.014)
Verge, et al. (2007). Agricultural production, greenhouse gas emissions and mitigation potential. Agricultural and forest meteorology, 142(2-4), 255-269. (Doi: 10.1016/j.agrformet.2006.06.011)

