DOI: 10.1002/adsc.201200059

Palladium-Catalyzed 1,4-Addition of Carboxylic Acids to Butadiene Monoxide

Akiyuki Hamasaki,[a] Shuhei Maruta,[a] Aki Nakamura,[a] and Makoto Tokunaga[a,b,]*

[a] Department of Chemistry, Kyushu University, 6-10-1 Hakozaki, Higashi-ku, Fukuoka 812-8581, Japan
Fax: (+81)-92-642-7528; phone: (+81)-92-642-7528; e-mail: mtok@chem.kyushu-univ.jp
[b] International Research Center for Molecular Systems (IRCMS), Kyushu University, Moto-oka 744, Nishi-ku, Fukuoka 819-0395, Japan

Received: January 21, 2012; Revised: April 29, 2012; Published online: July 31, 2012

Supporting information for this article is available on the WWW under http://dx.doi.org/10.1002/adsc.201200059.

Abstract: Palladium complexes catalyze the 1,4-addition of acetic acid to butadiene monoxide to give 4-hydroxybut-2-en-1-yl acetate. The highest 1,4-/1,2-addition selectivity of 18.9 was achieved. The reaction seems to proceed *via* a Wacker-like mechanism.

Keywords: 1,4-addition; butadiene monoxide; carboxylic acids; palladium

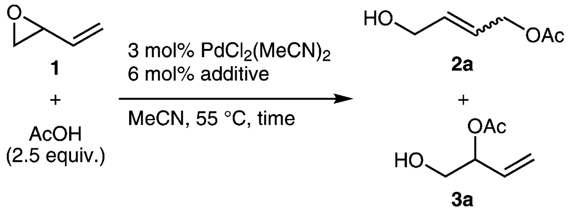
Vinyloxiranes are useful substrates for organic synthesis and have high reactivities toward addition reactions with various nucleophiles.[1] Particularly, the facile formation of π-allyl Pd-complexes by the cleavage of C-2−O bonds and successive addition to the 4-position provides 1,4-addition products.[2] When carboxylic acids were used as nucleophiles, 1,4-bis-oxygen-functionalized 2-alkenes have been obtained and utilized for natural product syntheses.[3] Although this reaction has a relatively wide scope for internal diene monoxides, few patents are found on unsubstituted 1,3-butadiene monoxide and the selectivities for the 1,4-addition product were low (1,2- *vs.* 1,4-addition for ~1:1).[4a,b,c] Querci reported an efficient catalytic system using acid anhydrides as nucleophiles and phosphine ligands to give the 1,4-addition product selectively.[4d] However, carboxylic acids are preferable to acid anhydrides in the point of atom efficiency. The product 1,4-butanediol derivatives are very important materials in the petroleum and coal chemical industries for the production of basic chemicals such as THF, γ-butyrolactone, and synthetic fibres.[5] Since we have been interested in oxygen nucleophile addition to various organic molecules,[6] this time we carried out a study to achieve selective the 1,4-addition of carboxylic acids to butadiene monoxide.

Various metal complexes were examined as catalysts in the acetic acid addition to butadiene monoxide (Table S-1 in the Supporting Information). Ir, Ru, Au, Cu and Pt complexes gave undesired **3** as major products (Table S-1 in the Supporting Information, entries 2–8). Similar to the results reported in the patents,[4a,b,c] Pd(0) catalyzed the reaction smoothly but the selectivity of **2**/**3** was 0.6 (Table S-1 in the Supporting Information, entry 9). Several Pd(II) complexes were tested and among them, $PdCl_2(MeCN)_2$ gave **2** as major product although the yield was only 20% (Table S-1 in the Supporting Information, entry 15). The **2**/**3** ratio was 4.0. Solvent screening was performed at this stage, toluene, THF, 2-propanol, pyridine, HMPA, DMSO, and dichloromethane gave almost no conversions or low selectivity of **2**. The reaction in acetonitrile and amidic solvents gave generally preferable yields and selectivities.

Then the effect of additive was examined with acetonitrile as solvent. The addition of Ag salts did not improve the reactivity and selectivity (Table 1, entries 1–3). By the addition of Li, Na, K and Cs salts, both the yield and selectivity were improved. The addition of basic salts generally increased the yield and bromide salts raised the selectivity. The combination of basic salts and bromide salts such as K_3PO_4/LiBr improved both together (Table 1, entry 13). Since the addition of bromide salts gave better results, the reaction with $[PdBr_2(MeCN)_2]$ in the presence of K_3PO_4/LiBr was examined and resulted in a good selectivity **2**/**3** = 10.7 (Table 1, entry 17).

Further optimization of the reaction conditions was carried out with this catalyst system (Table 2). Here, the reactions without solvent gave improved chemical yields and at lower temperatures also gave high selectivities. The highest total yield of **2** and **3** was 97% at 35 °C and the selectivity was 6.4 (entry 4) Further lowerering of the temperature (5 °C) with LiBr gave a higher selectivity of 10.7 but the yield was 82% (entry 7). When LiBr was replaced with KBr, the best

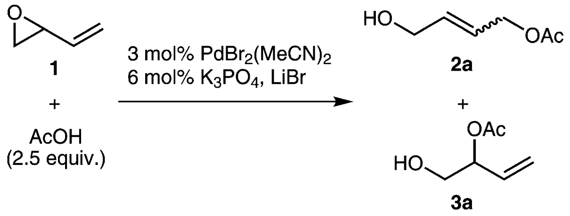
Table 1. Effect of additives.[a]



Entry	Additive	Time [h]	Yield[b] [%]		Ratio of **2a/3a**
			2a (*E*/*Z*)	**3a**	
1	AgOAc	24	17 (2.0/1)	9	1.8/1
2	AgTFA	2	9 (2.0/1)	3	3.5/1
3	AgOTf	2	0	2	0/1
4	LiOAc	2	28 (1.3/1)	4	6.4/1
5	Li_2CO_3	3	25 (1.1/1)	5	4.8/1
6	NaOAc	2	37 (1.3/1)	6	6.2/1
7	Na_2CO_3	2	39 (1.4/1)	6	6.1/1
8	KOAc	2.5	37 (1.3/1)	7	5.3/1
9	K_2CO_3	2	43 (1.5/1)	9	4.7/1
10	Cs_2CO_3	2	42 (1.4/1)	9	4.7/1
11	K_3PO_4	2	45 (1.7/1)	9	4.2/1
12	LiBr	24	30 (1.4/1)	6	5.3/1
13	K_3PO_4+LiBr	2	48 (1.4/1)	7	7.2/1
14	KF	2	31 (1.4/1)	6	5.5/1
15	NaI	1	0	0	
16	LiI	1	0	0	
17[c]	K_3PO_4+LiBr	2	50 (2.1/1)	5	10.7/1

[a] The reaction was carried out with butadiene monoxide (1 mmol), AcOH (2.5 equiv.) in 2 mL of acetnitrile under N_2.
[b] GC yield.
[c] $PdBr_2(MeCN)_2$ was used instead of $PdCl_2(MeCN)_2$.

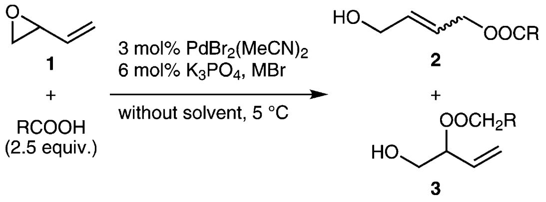
Table 2. Addition of acetic acid to butadiene monoxide catalyzed by palladium complexes under various reaction conditions.[a]

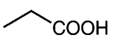
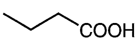
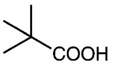
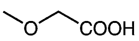
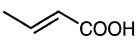
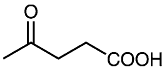
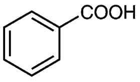


Entry	Temperature [°C]	Time [h]	Yield[b] [%]		Ratio of **2a/3a**
			2a (*E*/*Z*)	**3a**	
1[c]	55	2	50 (2.1/1)	5	10.7/1
2	55	2	70 (1.6/1)	14	5.1/1
3	45	2	75 (1.6/1)	13	5.9/1
4	35	2	84 (1.6/1)	13	6.4/1
5	25	2	72 (1.5/1)	10	7.0/1
6	15	2	80 (1.4/1)	8	9.5/1
7	5	3	75 (1.3/1)	7	10.7/1
8[d]	5	3	68 (1.3/1)	4	16.3/1
9	−15	24	0	0	

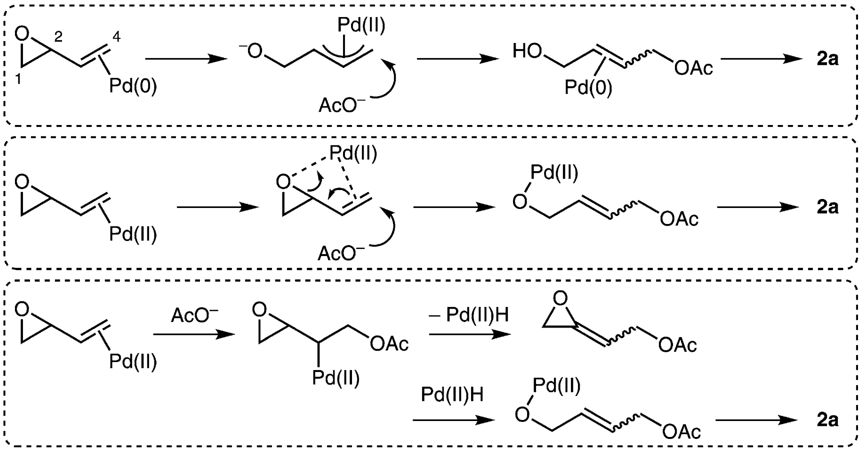
[a] The reaction was carried out with butadiene monoxide (1 mmol) and AcOH (2.5 equiv) without solvent under N_2.
[b] GC yield.
[c] MeCN (2 mL) was used as solvent.
[d] KBr was used instead of LiBr.

Table 3. Pd-catalyzed addition of various carboxylic acids to butadiene monoxide.[a]



Entry	RCOOH	MBr	Time [h]	Major product	Yield[b] [%] 2 (*E*/*Z*)	 3	Ratio of **2**/**3**
1		LiBr	3	**2b**	58 (1.1/1)	5	11.4/1
2		KBr	3	**2b**	49 (1.1/1)	3	17.6/1
3		LiBr	3	**2c**	49 (1.0/1)	4	13.5/1
4		KBr	3	**2c**	44 (1.0/1)	3	16.9/1
5		LiBr	24	**2d**	0	0	
6		KBr	24	**2d**	15 (1.5/1)	1	14.3/1
7		LiBr	1	**2e**	91 (1.8/1)	9	10.4/1
8		KBr	1	**2e**	79 (1.7/1)	6	12.4/1
9		LiBr	6	**2f**	52 (1.2/1)	5	10.9/1
10		KBr	6	**2f**	53 (1.1/1)	5	10.3/1
11		LiBr	10	**2g**	70 (1.3/1)	5	14.2/1
12		KBr	6	**2g**	60 (1.2/1)	3	18.9/1
13		LiBr	24	**2h**	0	0	
14		KBr	4	**2h**	32 (1.1/1)	4	7.1/1

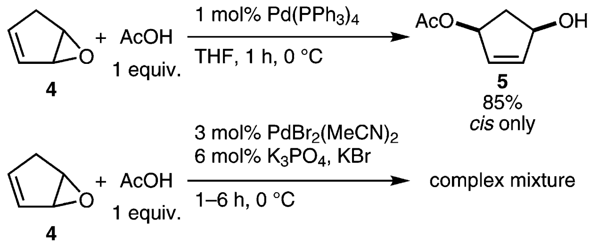
[a] The reaction was carried out with butadiene monoxide (1 mmol), carboxylic acid (2.5 equiv.) under N_2.
[b] GC yield.



Scheme 1. Possible mechanisms of palladium-catalyzed 1,4-addition of carboxylic acids.

selectivity (16.3) was observed although the yield was moderate (72%) (entry 8). Thus we decided upon the two optimized conditions; for the chemical yield: $[PdBr_2(MeCN)_2]+K_3PO_4/LiBr$ at 5 °C, and for the selectivity: $[PdBr_2(MeCN)_2]+K_3PO_4/KBr$ at 5 °C.

The reaction was surveyed with several different carboxylic acids under the optimized conditions (Table 3). Propanoic and butanoic acids gave slightly higher selectivities compared to acetic acid with somewhat lower yields (entries 1–4). When 2-methoxyacetic acid was used in the presence of $K_3PO_4/LiBr$, a 100% yield was achieved with the **2**/**3** ratio of 10 (entry 7). On the other hand, when 4-oxopentanoic acid was used in the presence of K_3PO_4/KBr, the **2**/**3** ratio reached to 19 (entry 12). Since the carboxylic acids with coordinating functionalities gave a better yield and selectivity (entries 7 and 12), an interaction of the acids to Pd may play an auxiliary role in this reaction. Benzoic acid gave lower yields and selectivities (entries 13 and 14).

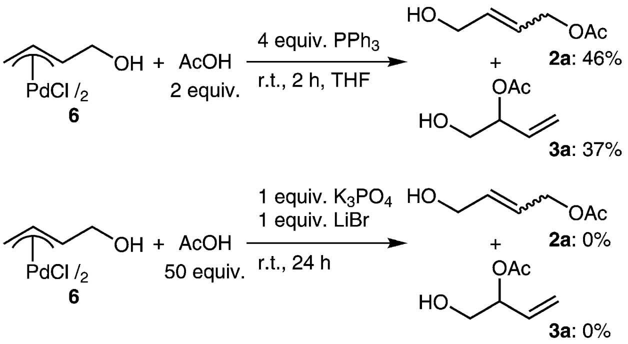


Scheme 2. Addition of acetic acid to cyclopentadiene monoxide with palladium-catalysts.

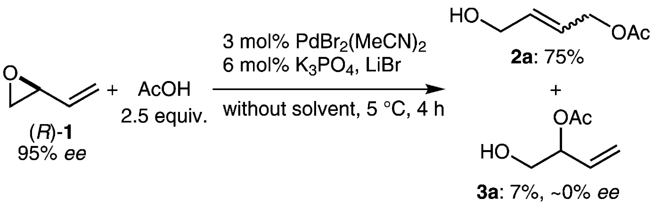
The widely accepted mechanism of this reaction for internal diene monoxides is depicted as **I** in Scheme 1.[2] The oxidative addition to the Pd(0) species by the cleavage of C–O bonds to form a π-allyl Pd intermediate followed by nucleophilic attack of acetic acid. However, since the precursor is a Pd(II) complex, alternative Wacker-like mechanisms **II** and **III** are also considered for this reaction.[7] The mechanism **II** includes 1,4-acetoxypalladation, in contrast, **III** proceeds *via* 1,2-acetoxypalladation, successive β-H elimination, and hydropalladation of epoxides. Since δ^+ is locating on the 2 and 4 positions, nucleophilic attacks on the 2 and 4 positions are suitable. Here, in general, hard Lewis acid activation preferred 2-attack, in contrast soft Lewis acid activation accelerated 4-attack. Recently, chelating control of the regioselectivity on Wacker oxidation of allyl-substituted substrates was studied.[8] The oxygen functionality at the allylic position induces terminal addition of nucleophiles. This chelating effect is also expected for our reaction, which supports the mechanism **II** and might enhance the **2**/**3** selectivity.

When the cyclic substrate **4** was reacted with nucleophiles, the *cis*-product was selectively formed with a Pd(0) catalyst as mentioned in literature reports (Scheme 2).[2] On the other hand, the Pd(II) catalyst optimized for this work afforded complex mixtures under several different conditions. This result suggests the active species is different from Pd(0) and Wacker-like mechanisms (**II** or **III**) seems to be valid.

A π-allyl Pd complex (**6**)[9] derived from **1** was examined for the stoichiometric addition of acetic acid (Scheme 3). In the presence of PPh$_3$, a similar result to the Pd(PPh$_3$)$_4$-catalyzed reaction was obtained. In contrast, the reaction with K$_3$PO$_4$/LiBr did not give **2a** and **3a**. Although a difference of reactivity between neutral and cationic π-allyl complexes should be considered, this result is consistent with the above expectation.



Scheme 3. Addition of acetic acid to a π-allyl Pd complex **6**.



Scheme 4. Addition of acetic acid to (*R*)-**1** with palladium catalysts.

However, Pd(0)/π-allyl Pd mechanism cannot be excluded completely. When optically active (95% *ee*) butadiene monoxide [(*R*)-**1**][10] was used, the enantiomeric excess of obtained **3a** was 0% (Scheme 4), while the unreacted substrate kept the initial *ee* value. This result suggests that **3** was not formed *via* a simple epoxide ring opening mechanism. A plausible pathway to racemic **3** is the π-allyl Pd mechanism including an equilibrium with the corresponding σ-allylpaladium complexes.[11] The other possibility is the indirect formation such as isomerization of **2** into **3** *via* π-allyl Pd or 1,3-acetoxy shift. Actually, when **2** was exposed to reaction conditions at 55 °C, gradual isomerization to **3** was observed. However, the isomerization was completely suppressed at 5 °C. Therefore, the formation of **3** under the conditions (at 5 °C) *via* isomerization is unlikely. Since the unreacted substrate was not racemized, it is also unlikely that the reversible formation of a carbocation at the 3-position or of a π-allyl Pd complex occurs. Although there is a possibility that halohydrin, which is reversibly formed by a treatment of butadiene monoxide with lithium halide and AcOH,[12] is involved in the reaction path, the unaltered enantiopurity of substrate **1** negates this assumption.

At this moment we think a Wacker-like mechanism (**II** or **III**) is plausible for the major product (**2**) whereas a Pd(0) π-allyl mechanism is likely for the minor product (**3**). The effect of the Br$^-$ concentration to the **2**/**3** selectivity might be attributable to the inhibition of Pd(0) formation and aggregation by [PdBr$_4$]$_2^-$ complexation.

In the mechanistic studies of the Wacker oxidation of ethylene on the effect of Cl$^-$ concentration, it has been proposed that the higher Cl$^-$ concentration brings outer sphere attack of water while a lower concentration leads to inner sphere attack.[13a,b] However, recent theoretical studies revealed that outer sphere attack of water is predominant irrespective of Cl^- concentration.[13c,d] According to these studies, the Br^- concentration presumably does not change inner/outer attack. On the other hand, a higher Br^- concentration increases the amount of $[PdBr_4]_2^-$ and prevents Pd(0) formation. Since Pd(II) metal prefers softer Br^- than Cl^-, the former gave the better results.

In conclusion, the highly selective 1,4-addition of carboxylic acids to butadiene monoxide has been achieved with Pd(II) catalysts. The highest ever 1,4-/1,2- selectivity of 18.9 was achieved. In contrast to Pd(0)-catalyzed 1,4-addition of substituted butadiene monoxide which proceeds *via* a π-allyl Pd mechanism, the present reaction seems to proceed *via* a Wacker-like mechanism. The reaction provides useful 1,4-dioxygen-functionalized intermediates for basic chemicals production.

Experimental Section

Typical Procedure for Acetic Acid Addition to 1 (Table 2, entry 7)

A mixture of $PdBr_2(MeCN)_2$ (10.4 mg, 0.03 mmol), K_3PO_4 (12.7 mg, 0.06 mmol) and LiBr (5.1 mg, 0.06 mmol) was placed in a screw-cap tube. To this screw-cap tube, acetic acid (150 mg, 2.5 mmol), triglyme[14] (45 μL, 0.25 mmol) as an internal standard, and butadiene monoxide (70 mg, 1 mmol) were added. The mixture was stirred at 5 °C for 3 h. Yields of the products were determined by GC analysis relative to an internal standard.

Supporting Information

Additional experimental procedures and spectral data are available as Supporting Information.

Acknowledgements

The present work is supported by a Grant-in-Aid for Global-COE program, "Science for Future Molecular Systems", Scientific Research (A) (No. 20245014) from the Ministry of Education, Culture, Science, Sports and Technology of Japan. We appreciate a financial support from Mitsubishi Chemical Corporation.

References

[1] C. Jaime, R. M. Ortuño, J. Font, *J. Org. Chem.* **1988**, *53*, 139–141; B. Olofsson, U. Khamrai, P. Somfai, *Org. Lett.* **2000**, *2*, 4087–4089; J. Muzart, *Tetrahedron* **2005**, *61*, 5955–6008; M. Kimura, R. Mukai, T. Tamaki, Y. Horino, Y. Tamaru, *J. Am. Chem. Soc.* **2007**, *129*, 4122–4123; J. Muzart, *Eur. J. Org. Chem.* **2011**, 4717–4741.

[2] B. M. Trost, G. A. Molander, *J. Am. Chem. Soc.* **1981**, *103*, 5969–5972; B. M. Trost, S. R. Angle, *J. Am. Chem. Soc.* **1985**, *107*, 6123–6124; T. Tsuda, M. Tokai, T. Ishida, T. Saegusa, *J. Org. Chem.* **1986**, *51*, 5216–5221; M. Gagliardo, N. Selander, N. C. Mehendale, G. van Koten, R. J. M. K. Gebbink, K. J. Szabó, *Chem. Eur. J.* **2008**, *14*, 4800–4809; P. Zhang, J. P. Morken, *J. Am. Chem. Soc.* **2009**, *131*, 12550–12551.

[3] D. R. Deardorff, D. C. Myles, K. D. MacFerrin, *Tetrahedron Lett.* **1985**, *26*, 5615–5618; Y. Kobayashi, M. Asano, S. Yoshida, A. Takeuchi, *Org. Lett.* **2005**, *7*, 1533–1536; Y. Kobayashi, S. Yoshida, M. Asano, A. Takeuchi, H. P. Acharya, *J. Org. Chem.* **2007**, *72*, 1707–1716;.

[4] a) S. A. Godleski, *PCT Int. Appl.* WO 8902883, **1989**; b) R. Pinkos, R. Fischer, *German Patent Application* DE 94-4429690, **1995**; c) M. Retboll, H. Ono, *Japan Patent Application* JP 2000-258360, **2000**; d) D. Bianchi, C. Querci, M. Ricci, R. Santi, *Tetrahedron Lett.* **1997**, *38*, 3081–3084.

[5] K. Weissermel, H.-J. Arpe, *Industrial Organic Chemistry*, 4th edn., Wiley-VCH, Weinheim, **2003**; H. A. Wittcoff. B. G. Reuben, J. S. Plotkin, *Industrial Organic Chemicals*, 2nd edn., Wiley-VCH: Hoboken, **2004**.

[6] A. Nakamura, M. Tokunaga, *Tetrahedron Lett.* **2008**, *49*, 3729–3732; H. Itoh, E. Yamamoto, S. Masaoka, K. Sakai, M. Tokunaga, *Adv. Synth. Catal.* **2009**, *351*, 1796–1800; T. Hirai, A. Hamasaki, A. Nakamura, M. Tokunaga, *Org. Lett.* **2009**, *11*, 5510–5513; A. Hamasaki, A. Yamamoto, H. Ito, M. Tokunaga, *J. Organomet. Chem*, **2011**, *696*, 202–210; A. Nakamura, A. Hamasaki, S. Goto, M. Utsunomiya, M. Tokunaga, *Adv. Synth. Catal.* **2011**, *353*, 973–984; E. Yamamoto, A. Nagai, A. Hamasaki, M. Tokunaga, *Chem. Eur. J.* **2011**, *17*, 7178–7182.

[7] P. M. Henry, *J. Am. Chem. Soc.* **1972**, *94*, 7305–7310; O. S. Andell, J.-E. Bäckvall, *J. Organomet. Chem.* **1983**, *244*, 401–407.

[8] S.-K. Kang, K.-Y. Jung, J.-U. Chung, E.-Y. Namkoong, T.-H. Kim, *J. Org. Chem.* **1995**, *60*, 4678–4679; J. Muzart, *Tetrahedron* **2007**, *63*, 7505–7521; B. W. Michel, A. M. Camelio, C. N. Cornell, M. S. Sigman, *J. Am. Chem. Soc.* **2009**, *131*, 6076–6077; B. W. Michel, J. R. McCombs, A. Winkler, M. S. Sigman, *Angew. Chem.* **2010**, *122*, 7470–7473; *Angew. Chem. Int. Ed.* **2010**, *49*, 7312–7315.

[9] J. Kjellgren, J. Aydin, O. A. Wallner, I. V. Saltanova, K. J. Szabó, *Chem. Eur. J.* **2005**, *11*, 5260–5268.

[10] M. Tokunaga, J. F. Larrow, F. Kakiuchi, E. N. Jacobsen, *Science* **1997**, *277*, 936–938.

[11] a) B. M. Trost, R. C. Lemoine, *Tetrahedron Lett.* **1996**, *37*, 9161–9164; b) R. Prétôt, A. Pfaltz, *Angew. Chem.* **1998**, *110*, 337–339; *Angew. Chem. Int. Ed.* **1998**, *37*, 323–325; c) B. M. Trost, R. C. Bunt, R. C. Lemoine, T. L. Calkins, *J. Am. Chem. Soc.* **2000**, *122*, 5968–5976; d) B. M. Trost, W. Tang, *Org. Lett.* **2001**, *3*, 3409–3411; e) similar π-allyl Pd intermediates are also considered for allylic acetoxylation: H. Grennberg, J. E. Bäckvall, *Chem. Eur. J.* **1998**, *4*, 1083–1089.

[12] J. S. Bajwa, R. C. Anderson, *Tetrahedron Lett.* **1991**, *32*, 3021–3024.

[13] a) O. Hamed, P. M. Henry, *Organometallics* **1997**, *16*, 4903–4909; b) O. Hamed, P. M. Henry, C. Thompson, *J. Org. Chem.* **1999**, *64*, 7745–7750; c) A. Comas-Vives, A. Stirling, A, Lledós, G, Ujaque, *Chem. Eur. J.* **2010**, *16*, 8738–8747; d) N. N. Nair, *J. Phys. Chem. B* **2011**, *115*, 2312–2321.

[14] There is a possibility that triglyme have some influence on the product selectivity by acting as a ligand. However, similar yields of entries 3 and 7 in Table 2 were obtained when *o*-xylene (20 μL) was used as an internal standard instead of triglyme.